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## Experimental investigation of failure in thin rings subjected to uniform external pressure

Demyttenaere, Jules Henry; Norris, William J.

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# EXPERIMENTAL INVESTIGATION OF FAILURE IN THIN RINGS SUBJECTED TO UNIFORM EXTERNAL PRESSURE

Jules Henry Demyttenaere
and
William Joseph Norris







### EXPERIMENTAL INVESTIGATION OF FAILURE IN THIN RINGS SUBJECTED TO UNIFORM EXTERNAL PRESSURE

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JULES HENRY DEMYTTENAERE, LTJG., U.S.NAVY B.S., United States Naval Academy

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EXPERIMENTAL INVESTIGATION OF FAILURE IN THIN RINGS SUBJECTED / TO UNIFORM EXTERNAL PRESSURE

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JULES HENRY DEMYTTEWAERE and WILLIAM JOSEPH NORRIS



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ABRE, LTJG., U.S.NAVY cates Naval Academy (1949)

and

WILLIAM JOSEPH NORRIS, LTJG., U.S.NAVY B.S., United States Naval Academy (1949)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
NAVAL ENGINEER

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May, 1954



EXPERIMENTAL INVESTIGATION OF FAILURE IN THIN RINGS SUBJECTED TO UNIFORM EXTERNAL PRESSURE

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JULES HENRY DEMYTTENABRE, LTJG., U.S.NAVY B.S., United States Naval Academy (1949)



TITLE: EXPERIMENTAL INVESTIGATION OF FAILURE IN THIN RINGS SUBJECTED TO UNIFORM EXTERNAL PRESSURE

AUTHORS: J. H. Demyttenaere, LTJG., U.S.N., and W. J. Norris, LTJG., U.S.N.

Submitted to the Department of Naval Architecture and Marine Engineering on May 24, 1954, in partial fulfillment of the requirements for the degree of Naval Engineer.

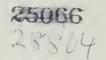
#### ABSTRACT

The object of this thesis was to investigate experimentally the strain distributions and ultimate failures in thin circular and non-circular aluminum rings subjected to uniform external pressure.

A test apparatus was designed to permit the application of hydraulic pressure to the outer circumference of a ring placed between two sheets of Plexiglas. The small clearance between the edges of the ring and the Plexiglas was sealed by a continuous rubber gasket of slightly greater width fitted around the outer circumference of the ring. Except for friction at the gasket-Plexiglas interface, the ring was free of restraint.

Nine rings of aluminum alloy, 615-T6, were tested to collapse: the variable in this series was out-of-roundness. Correlation between measured and predicted strains was obtained in five of the six rings in which the assumptions of the prediction were valid. A somewhat arbitrary strain distribution was observed in the two most circular rings. The four rings of moderate out-of-roundness collapsed very near predictions based upon a criteria related to the maximum stress level in the outer fibers while the three rings of relatively large out-of-roundness failed at pressures somewhat higher than predicted. The two most circular rings collapsed near a computed pressure when the minimum rather than average section thickness was used in the calculation. Collapse pressures were predicted most accurately when the stress used in conjunction with the failure criteria was defined by the point on the stressstrain curve at which marked non-linearity occurred.

An analysis of the results indicates that strain distributions in an out-of-round ring loaded by uniform external pressure can be predicted with satisfactory



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accuracy provided the assumptions made in the prediction are satisfied; namely, that the thickness to diameter ratio be the order of 0.0285 and that the initial configuration assumed is actually predominate. A failure criteria based upon the stress level in the outer fibers will, when the assumptions above are fulfilled, predict collapse quite accurately in rings of out-of-roundness to thickness ratio between 0.10 and 0.30. At larger values of out-of-roundness the criteria is conservative but not over cautious.

It is recommended that the experimentation be extended to include a quantitative investigation of the effects of deviations from a basic two lobe out-of-roundness such as might be obtained in a practical situation. Such an investigation should be conducted using rings of constant thickness in order to avoid many of the unnecessary complications encountered in the analysis of data obtained in this thesis.

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Cambridge, Massachusetts May 24, 1954

Professor Leicester F. Hamilton Secretary of the Faculty Massachusetts Institute of Technology Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Naval Engineer, we submit herewith a thesis entitled, "Experimental Investigation of Failure in Thin Rings Subjected to Uniform External Pressure."



#### ACKNOWLEDGMENTS

The authors wish to express their appreciation to those individuals at the Massachusetts Institute of Technology, Boston Naval Shipyard, and the David Taylor Model Basin, who so generously gave their time and advice so that the objectives of this thesis might be accomplished.

Specifically the authors wish to thank

Dr. E. Wenk, Jr., of the David Taylor Model Basin, who

originally posed many of the problems involved;

Dr. W. W. Murray, of the Massachusetts Institute of

Technology, and his assistant Mr. Peter Stein for their

most helpful advice on a multitude of details.

The authors are particularly grateful to their Thesis Supervisor, J. H. Evans, Assistant Professor of. Naval Architecture, Massachusetts Institute of Technology, for his encouragement and advice during the progress of the thesis.

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### SYMBOLS AND ABBREVIATIONS

The following symbols and abbreviations are used throughout this report:

- b = Width of ring, in inches
- D = Mean diameter measured to neutral axis, in inches
- E = Modulus of elasticity initial slope of stressstrain curve, psi.
- $\mathcal{E}$  = Compressive strain, inches/inch or micro-inches/inch.
- h = Thickness of ring, in inches.
- I = Moment of inertia of ring cross-section about neutral axis, in in.4
- P = Pressure, psi.
- Pority = Collapse pressure of a circular ring, psi.
  - psi. = Pounds per square inch.
    - R = Mean radius to neutral axis of ring, in inches.
    - Ro = Mean radius to outer circumference of ring, in inches.
    - G = Compressive stress, psi.
    - $\sigma_y = 0.2\%$  proof stress, psi.
      - $\theta$  = Angular coordinate to designate positions on ring, in degrees.
    - uo = Two-lobe out-of-roundness, maximum deviation from a true circle of the same perimeter as the twolobe configuration, in inches.
    - u1 = Three-lobe out-of-roundness, inches
    - up = Four-lobe out-of-roundness, inches

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- $\mathcal{E} = 0$  appreciate strain, intopes, inch or incompanyings.
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### INTRODUCTION

### Objective

The objective of this thesis is to investigate experimentally the strain distributions and ultimate failures obtained in thin circular and non-circular aluminum rings subjected to uniform external pressure.

Background

The slender column in axial compression is generally cited as the classic example of a buckling failure. The behavior of such axially loaded columns was subjected to an early theoretical analysis, and at the same time numerous investigators supplied experimental data relevant to the problem. The experimentation served two purposes. First, the conclusions substantiated the basic concepts and accuracy of the theoretical analysis. Second, certain practical aspects of the problem were magnified. Thus, through an analysis of experimental data and an appreciation of the difficulty in obtaining a perfectly loaded column, Moncrieff (1) was able to propose a practical criteria for column strength which included the assumption of an inherent eccentricity.

The failure of thin rings subjected to uniform external pressure is analogous to the buckling of columns.

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The buckling of such uniformally loaded rings has been treated theoretically by investigators as early as Levy (2) and as recent as Boresi (3). In addition a clear presentation of the problem is given by Timoshenko (4). Despite the extensive theoretical analysis, experimentation has been lacking. In a search of the literature, the authors found no instance of a ring being collapsed experimentally under a uniform external load.

The lack of experimental data relative to the ring problem may be partially explained by the following:

- The use of the ring as a structural member is not so widespread as the column. Hence the need for usable data was not pressing.
- 2. Many of the conclusions formulated as a result of column analysis were applicable to the ring problem.
- The buckling of a cylinder subjected to external pressure is closely related to the buckling of a ring. Obviously much of the data gleaned from failure of cylinders also applies to rings. The collapse of a cylinder may be effected simply and conveniently in the laboratory.
- 4. A free ring loaded with uniform external pressure offers a difficult problem in the design of a test apparatus.

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- 4. A Tree ring leaded with welform external presents of a presto of a delitable of a state design of a tent apparente.

Despite the apparent validity of the theoretical analysis of ring buckling and the availability of related experimental data, there is a need for experimentation devoted specifically and directly to the collapse of a thin ring. This need arises not merely from the satisfaction to be gained by proving the validity of the concepts or assumptions of the pertinent theory but from a desire to obtain a practical perspective. Thus, some peculiarity of the ring problem may yet be unrecognized; practical expedients such as the assumption of an inherent out-of-roundness may be necessary. Furthermore, there is need for a substantial and tested criteria of failure which may or may not be related to the stress level at the inner or outer surface of the ring. It is to be appreciated that in out-of-round rings, failure results when stable equilibrium is not possible between an internal and external bending moment and is not a direct result of some specified stress in the outer fibers. In addition, the ring provides a convenient means of studying and evaluating out-of-roundness not only in rings but also in cylinders. In a theoretical approach out-of-roundness may be represented very simply by a Fourier series; there is need for a simple, yet reliable, measure of out-of-roundness which has a practical value. Problem

The authors have undertaken the task of obtaining and

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evaluating experimental data of the type referred to above.

Implied in this assignment are the following specific problems:

- The design and construction of a test apparatus which will permit the application of a uniform external load to an essentially free ring.
- 2. The instrumentation of a ring such that the strain distribution may be determined.
- 3. A comparison of measured strain distribution and failure loads with theoretical predictions.
- 4. A review of experimental results for the purpose of pointing out the practical aspects of the ring buckling problem.

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### PROCEDURE

### Outline

The procedure followed in this thesis is to be presented under the following subheadings:

- (a) Selection of Material for Construction of Rings
- (b) Manufacture of Rings
- (c) Ring Dimensions and Instrumentation
- (d) Design and Manufacture of Test Apparatus
- (e) Proof Test of Apparatus
- (f) Test of Rings
- (g) Test of Compression Specimens
- (h) Evaluation of Data
- (i) Correlation of Data

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### Selection of Material for Construction of Rings

Rings were machined from a length of 9" aluminum alloy (61S-T6)tubing of 1/4" wall thickness. The actual outside diameter as determined by the authors was 9.016".

The decision to use aluminum alloy test rings was based upon the following considerations:

- 1. To properly correlate measured and predicted strain distributions it was necessary to select a material in which the stress-strain relationship was essentially linear over a considerable range of stress. Aluminum alloy 61S-T6 was suitable in this respect since the estimated 0.2% proof stress was 40,000 psi. (5).
- 2. The predicted failure pressures for rings of reasonable diameter and thickness were satisfactory. Reasonable dimensions were defined as any diameter and thickness of tubing or pipe which was available and which could be accommodated by the facilities in the testing laboratory. A relatively high failure pressure was desirable in that sufficient accuracy could be obtained without the use of an extremely sensitive pressure measuring device.

  Yet the maximum pressure should not be so high as to require an excessively complicated and expensive test apparatus.

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- The needints find thiciness were only occord, remained a commission of the second thickness were only occord. Assessments finenerous were defined as one dispets and and thickness of tabins or pipe which was evaluable and makes social as anosanotated by the institution and institution in the the casting lemperature. A relativistic high respects were described in the thickness presents were described and not the anishes of or extracted anishes presents are should not to see that as the isquires an expensively consistent and arguments.

### Manufacture of Rings

The aluminum alloy tubing as received was cut into sections of 2 1/2" to 3 1/2" lengths. Out-of-roundness was then intentionally introduced in the majority of these pieces by placing the individual sections in a loading machine and applying a load. When the desired permanent set had been obtained the load was removed. Since essentially circular rings were to be machined from the remainder of the sections no deformation was introduced. In this manner a range of out-of-roundness was obtained which varied from  $u_0 = 0.007$ " in the tubing as received to  $u_0 = 0.296$ " in the section with the greatest intentional deformation.

As a result of the permanent set imposed, there existed an unknown residual stress at points stressed above the elastic limit. To insure linearity of measured strains over a maximum range, the sections were subjected to a solution heat treatment followed by the precipitation heat treatment required to obtain alloy 61s-T6. Uniformity of properties was insured by heat treating, as a group, all sections plus the material from which compression specimens were to be manufactured.

Wooden plugs about 1 inch in thickness were tailored to fit into one end of each section in order to facilitate final machining and to avoid distortion caused by the clamping jaws of the lathe. Rings of specified width were

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then cut from the sections; this width was determined by a direct measurement of the clearance between the surfaces of the annular test chamber in the completed test apparatus. The rings as cut were generally 0.444" to 0.446" in width, the maximum deviation for a single ring being 0.001". The thickness of the rings remained the same as received. Ring Dimensions and Instrumentation

The outside diameter of each ring was found by fitting a wire 0.01" in diameter around the outer circumference. The wire was scribed and then measured between the scribe marks on a 36" steel rule. An outside radius was computed by dividing the measured circumference by  $2\,\mathrm{M}$  and correcting for the thickness of the measuring wire. All radii thus determined were averaged to give a mean outside radius (4.508) for use in the computations.

The measuring wire was scribed at intervals of 30 degrees of arc length and again fitted around each ring. The scribe marks were transferred to the aluminum alloy. For those rings in which deformation had been introduced care was taken to locate one of the scribe marks as close as possible to the point of maximum diameter. The twelve stations so determined were designated 0° through 330° in 30° increments, with 0° at a point of maximum diameter. The thickness and width at each station were measured with small micrometers

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while the outside diameter was measured at stations and half stations with large outside micrometers.

Baldwin SR-4, type A-7, strain gages were cemented to the inner surface of the ring at each station with the gage length along the circumference. Photograph No. 1 shows the strain gages in position on the ring after the leads had been soldered in place. The leads were passed through the bottom of the test apparatus and connected to the multiple selector switchbox which in turn was connected to the strain indicator. The dummy gage was attached to a scrap piece of aluminum alloy which was placed in the vicinity of the test apparatus. Leads from the dummy were connected to the switchbox.

### Design and Manufacture of Test Apparatus

The design of the apparatus and its associated equipment can be understood from photographs Nos. 2, 3, 4 and Figures I and II. The bucket pump had been previously tested up to a pressure of 1600 psi and was considered to be of sufficient capacity to supply oil to the pressure chamber enclosing the ring.

The test apparatus was made by the Mechanical Engineering Department machine shop at the Massachusetts Institute of Technology to plans and specifications furnished by the authors. It is to be noted that provision was made for a ting our another of harmens are separate ablieve and oline entropy and the substance extends of the substance entropy and the substance entropy and

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Photograph No. 1
RING WITH STRAIN GAGES AND LEADS



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Photograph No. 2
TEST APPARATUS



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Photograph No. 3
TEST APPARATUS

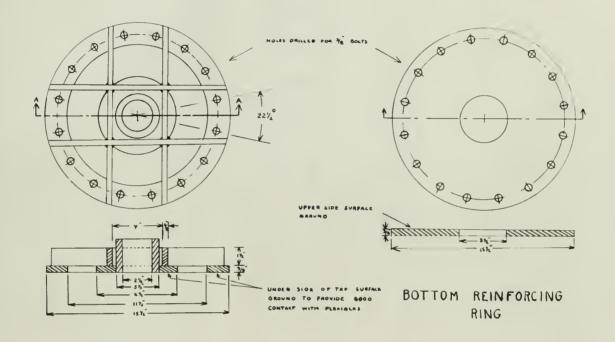


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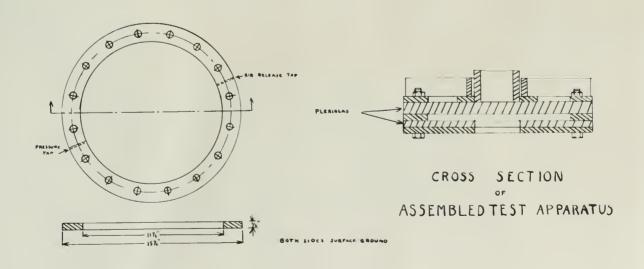
Photograph No. 4
TEST APPARATUS WITH CATHETOMETER MOUNTED



### FIGURE I TEST APPARATUS

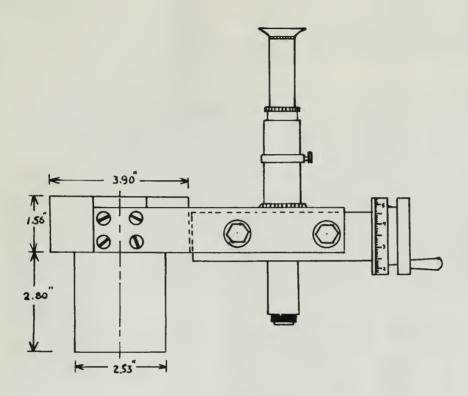


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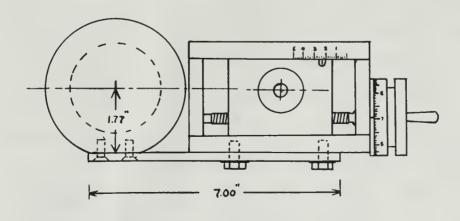




# FIGURE # CATHETOMETER MOUNTING

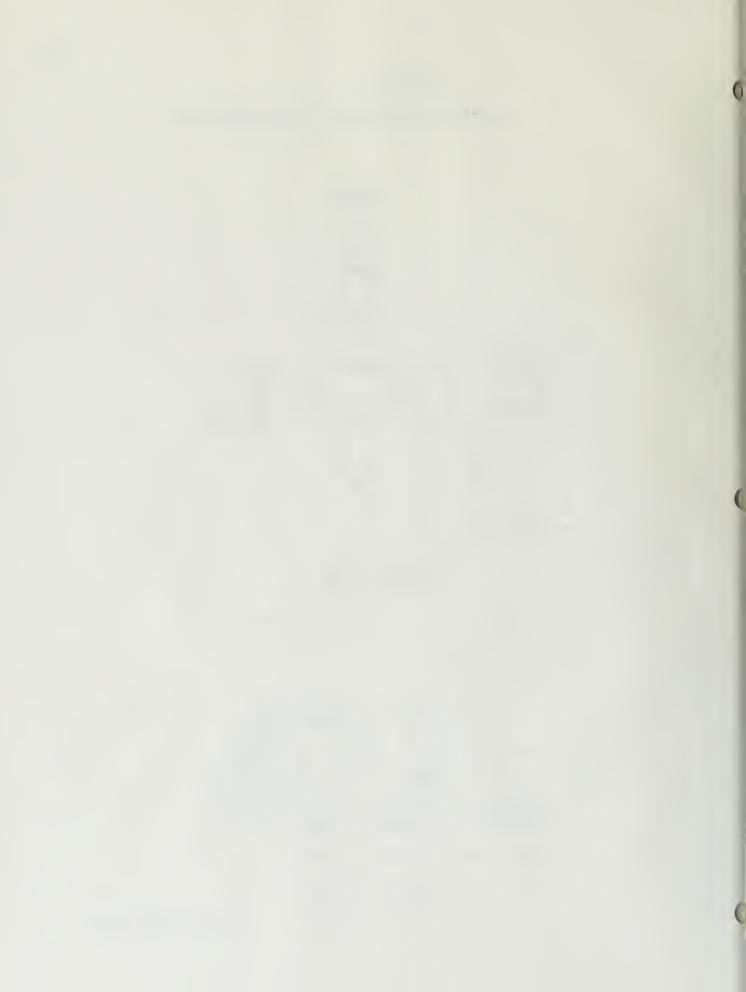


SIDE VIEW



TOP VIEW

7/24/54 YAD- WJN



viewing chamber which would permit inspection of the rings during application of pressure. The pressure gage was furnished by the Department of Mechanical Engineering, MIT, and calibrated by the authors.

### Proof Test of Apparatus

Upon completion of the test chamber by the machine shop, the complete test apparatus as indicated in Photographs

Nos. 2, 3, and 4 was assembled and proof tested by the authors.

Two preliminary test rings were machined from a section of the original aluminum tubing for use in this phase of the testing.

To maintain pressure in the test chamber behind the aluminum rings, a gasket of width slightly greater than 1/2" was placed around the outer circumference of the ring; several types of gasket material were tried. In each case the gasket material was cut to size, glued to the outer surface of the ring, and bound lightly by several strands of light string lying along the circumference. The ring was then placed in the test apparatus and the upper Plexiglas surface and top web assembly were boilted down. Oil was pumped into the test chamber with the bucket pump and the air vented through the air release tap. Pressure was built up behind the ring in the test chamber until, in most cases, the gasket material extruded between the Plexiglas surfaces

visuing anamous water would parell imagestion of the sings during application of pressure. Ins pressure sage was rightened by the Department of Geometrical Sagineering, ATE, and calibrated to the subnorm.

## ASSESSMENT TO PERSONAL

Open completion of the seet amender by the manning anorated complete test apparatus as indicated in These properties.

Nos. 2, 3, and 4 was assembled and proof tosted or the sathers.

Two preliminary test rings were sechioed from a saction of the original size into tubing for ase in this phase of the testing.

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and the edges of the ring. As a result of these trials, the best gasket material for sealing the ring edges appeared to be a rubber gasket cut from an ordinary truck tire inner tube approximately 9" in diameter. This type of gasket was used throughout the remainder of the proof tests and the final tests. Pressures up to 875 psi. were maintained in the test chamber using this gasket.

An Ames dial gage was mounted on the steel web assembly midway between the top inner and outer backing up rings to determine the maximum deflection of the Plexiglas surface as pressure was applied. A maximum deflection of 0.007" occurred at 875 psi. The deflection occurring at 500 psi. was of the order of 0.004".

It became apparent during these tests that some type of lubricant was necessary to eliminate or reduce to a minimum the friction between the rubber gasket and the Plexiglas surfaces. Several types of lubricant were tried and the best found to be black rubber-to-metal cement. Strains at a particular station were found to vary with the lubricant and gasket material when the same pressure was applied.

The cathetometer was mounted during the preliminary test phase and attempts were made to take deflection readings. Unfortunately the cathetometer proved impractical as a means

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The outherpreser was nounted outle including the prolimenty test press and extensive were made to take deficition recollars. Outfortunevely the cethetomorea proved improvious as a securi

of reading deflection for several reasons, viz.

- 1. The slight deflection of the upper Plexiglas surface distorted the ring as seen through the eye piece of the cathetometer.
- 2. The use of black rubber-to-metal cement as a lubricant obscured the aluminum ring in the test chamber when oil was introduced.

The proof testing period was of infinite value to the authors in planning and carrying out the final tests of the circular and non-circular rings.

#### Test of Rings

One result of the proof testing was the formulation of a standard test procedure. As a consequence, the remainder of the tests were made in a minimum amount of time and with little difficulty.

Nine rings were tested in accordance with the following steps:

- 1. Leads were soldered to strain gages, threaded through the bottom of the test chamber, and connected to terminals on the back of the multiple selector switchbox.
- Black rubber-to-metal cement was applied to the rubber gasket and outer circumference of the ring. (Cement allowed to dry 3-5 minutes).
- 3. The rubber gasket was slipped around the outer

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- 1. The sizent inflection of the depart Pistifias Sortion of distinction of the size of the
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  - 2. Slept relief and outer Description of The First Colors of the F
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circumference of the ring and secured in place by four strands of light string. The gasket was adjusted so that the bevels extended an equal distance beyond the edges of the ring.

- 4. A thin film of #40 S.A.E. motor oil was applied to the inner Plexiglas surfaces.
- 5. The ring was centered in the test chamber.
- 6. The upper Plexiglas plate was slipped over the bolts and held down firmly by hand while the top web assembly was lowered into place.
- 7. All bolts were tightened.
- 8. Initial zero readings were set on all strain gages by adjusting switchbox set screws.
- 9. Air was vented through the air release tap while the test chamber was being filled with oil from the bucket pump.
- 10. Pressure in the chamber was increased in increments of 50 to 100 psi. depending upon the expected collapse pressure of the particular ring, 100 psi. increments being used for the more circular rings and 50 psi. increments for the more out-of-round rings. Strain gage readings were taken at each pressure increment.
- 11. Because the collapse of the more circular rings occurred rather quickly, the pressure was maintained

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momentarily at 5 psi. increments when the ring was near collapse. The collapse of a significantly out-of-round ring generally proceeded at a very slow rate. In this case the strain indicator was connected to read the maximum strain. Pressure was then increased in steps of 5 psi. or smaller, each pressure being maintained until the strain indication steadied.

12. When the strain indicator needle did not steady, failure occurred. Failures in the more circular rings were evidenced by an immediate drop in pressure and obvious deformations.

at which static strains could not be maintained. Complete failure of all rings was characterized by large, visible deflections regardless of the rate at which collapse proceeded; once complete failure occurred the ring would not again sustain collapse pressure.

### Test of Compression Specimens

The stress-strain curve for the material used in the fabrication of the rings for this investigation was determined by means of the "Single Thickness" compression test method. Three specimens of the aluminum alloy (61S-T6) were tested in the compression block as indicated in photographs Nos. 5 and 6. A complete description and

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Photograph No. 5

# HUGGENBERGER TENSOMETERS MOUNTED ON SPECIMEN IN COMPRESSION BLOCK



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Photograph No. 6

COMPRESSION BLOCK IN LOADING MACHINE



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bibliography for this method is given in reference (6). Compression tests in general are also discussed in reference (5).

### Evaluation of Data

All data obtained during the testing period can be grouped as follows:

- 1. Dimensions
- 2. Pressure at which strains were recorded
- 3. Pressure at which ring collapsed
- 4. Strain readings
- 5. Compression Specimen test data.

With one exception all dimensions recorded were taken with micrometers and can be considered accurate to 0.0005". The circumference, as determined by the scribed wire, was read to the nearest 1/128" on the steel rule. However, the authors felt that the accuracy was of the order of 1/64", one scale division. The accuracy of the average outside radius then becomes 0.0025".

The pressure gage was calibrated by the authors prior to the tests using a dead-weight tester. Two calibration runs were made using increasing pressures and two with decreasing pressures. The maximum deviation from true was found to be 4 psi.; the largest difference between an up reading and a down reading for the same true pressure was also 4 psi. Used in conjunction with a calibration curve

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Comparentian sees to general are also missuased an reference (5).

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the gage was considered to be accurate to ± 2 psi. although the accuracy was considerably better over most of the pressure range. During the tests the indicated pressure could be held fairly constant. An accuracy of plus or minus one half a scale division (±2 1/2 psi.) is probably conservative but will be assumed. The accuracy of the recorded pressures at which strain readings were taken then becomes ±5 1/2 psi.

With one additional consideration the above remarks also apply to the accuracy of the recorded collapse pressures. The collapse of rings with significant amounts of out-of-roundness occurred rather slowly. It would seem that the pressure could be inadvertently increased above the true collapse pressure, the only effect being an accelerated failure. However, in these instances the strain gage indicating the greatest strain was checked at small increments of pressure when the ring was near collapse. The pressure was not increased further until the strain gage reading steadied. In the authors' opinion the point of collapse was accurate to - 5 psi. for the very noncircular rings. On the otherhand, failure of the more circular rings occurred rather quickly. During the latter portion of a test run it was customary to pause momentarily at each 5 psi. increment of pressure. Again the authors estimate that the point of collapse was accurate to - 5 psi.

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Considering both the accuracy of the pressure reading and the point of failure, the recorded collapse pressure is believed to be within -10-1/2 psi. or +5-1/2 psi. of true.

The accuracy of the strain gages used, as stipulated by the manufacturer, was ± 2%. The transverse sensitivity correction was insignificant, being of the order of - 0.05%. An accuracy of one half the smallest scale division on the strain indicator, ± 5 micro-inches per inch, is generally assigned to the switchbox-indicator combination.

As a practical expedient plots of out-of-roundness which are presented in the RESULTS were derived in the following manner; the average diameter was subtracted from the measured diameter at stations and half stations; the difference was divided by two and plotted at diametrically opposite stations. It is to be appreciated that this method will define a symmetrical out-of-roundness curve but is truly representative of the initial configuration only when a symmetrical two lobe pattern predominates.

# Correlation of Data

The experimental data is compared to theoretical predictions based upon the following formula:

$$G = \frac{PR}{h} - \frac{6 PR u_0 \cos 2\theta}{h^2 (1 - P/P_{exit.})}$$
 (1)

Equation (1) was developed for the case of circular tubes in reference (4) but applies equally well to rings; the

Considering both the appulant of the presents realing and the polar of failure, the recorded unilars presents to be believed to be mittled - 10-1/2 pair of the control of

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assumptions made in the derivation may be found in the same reference. The major qualifications are that the ring be thin and that the initial configuration be given by  $(R + u_0 \cos 2 \theta)$ .

For purposes of computation the authors found it convenient to rearrange and modify equation (1)

$$G = \frac{PR_0}{h} + \frac{6 + Ru_0 h E \cos 2 \theta}{Eh^3 - 4PR^3}$$
 (2)

$$\mathcal{E} = \frac{PR_0}{E_h} + \frac{6 P Ru_0 h \cos 2 \theta}{E_h^3 - 4FR^3}$$
 (3)

Equation (2) was derived directly from equation (1) by the substitution of 3  $\rm Eh^3/l2$  for  $\rm P_{crit.}$ ,  $\rm R_o$  for R, and rearranging. Equation (3) is obtained by dividing equation (2) by E. The use of the outside radius,  $\rm R_o$ , instead of the radius to the neutral axis, R, in the hoop stress term seemed well taken but changed the predicted strains an insignificant amount.

A common criteria for failure is yielding of the outer fibers due to the addition of hoop stress and the maximum bending stress. Then as a basis for comparison of experimental and theoretical collapse pressures in those cases where the out-of-roundness pattern is  $u_0 \cos 2\theta$ , equation (2) can be reduced to

$$G_{\text{max.}} = \frac{FR_0}{h} + \frac{6 \ PR \ u_0 \ h \ E}{Eh^3 - 4PR^3}$$
 (4)

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$$\mathbf{\xi} = \frac{120}{2} + \frac{6 - 120}{6} + \frac{3}{2} = \frac{3}{2}$$
 (3)

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When  $\P_{\text{max}}$  is assumed to be equal to  $\P_{y}$ , the pressure as determined by equation (4) is then the theoretical collapse pressure.

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## III

## RESULTS

All results presented in this section were derived from data obtained by the authors.

Figure III is a plot of the data obtained during the compression tests of the aluminum alloy specimens and from which the value of Young's Modulus and the yield stress were determined.

Figure IV shows the results of the preliminary test which was made to determine the effect of various lubricants and gaskets upon strain. Lubricant #1 was black rubber-to-metal cement; Lubricant #2 was clear rubber cement. Gasket #1 had been used during the Proof Testing; Gasket #2 was of the same dimensions but had not been used previously.

Figures V, VIII, XI, XIV, and XVII show measured and theoretical circumferential strain distributions for one or more pressures. Theoretical curves are based upon equation (3).

Figures VI, IX, XII, XV, and XVIII are plots of out-of-roundness versus circumferential positions.

Figures VII, X, XIII, XVI, and XIX are plots of ring thickness versus circumferential position.

Figures XX-XXVI are a comparison of measured and predicted strains. The experimental points are an average of

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Provestical carposers-coxial etrain distributable for one or and presences. Thougestioni ouryes are based or a equation (3).

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strains read at the  $0^{\circ}$  and  $180^{\circ}$  positions, and  $90^{\circ}$  and  $270^{\circ}$  positions. The theoretical curves are based upon equation (3).

Figure XXVII shows experimental collapse points plotted on arguments of pressure and the ratio of out-of-roundness to average thickness.

Figure XXVIIIZ is a comparison of experimental collapse pressures with several theoretical predictions. All theoretical curves are based upon equation (4). They differ in that Curve A is plotted for  $T_{max} = T_y = 35,000$  psi. and  $T_{max} = T_y = 35,000$  psi.

Stratus vent or ten 2" one test vintations, in 900 And 2700 postrione ten threspectors convey and based ogon equation (3).

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FIGURE TIL STRESS STRAIN CURVE

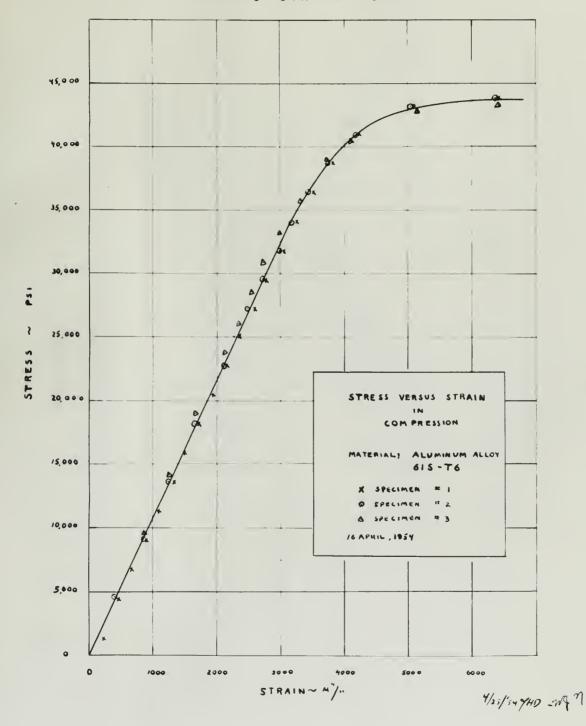




Figure I

CLACUMFERENTIAL STRAIN DISTAIBUTION FOR DIFFERENT LUBRICANTS AND GASKETS CLACKETS RING NO.-PAELIMINAAY TEST

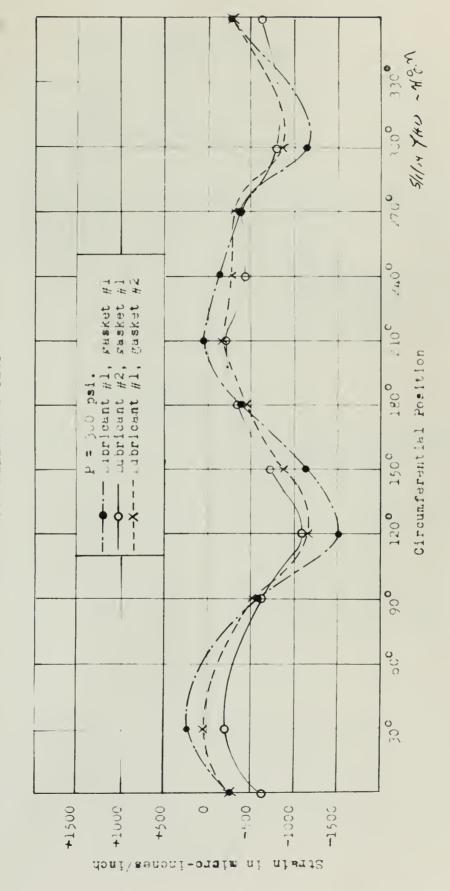




Figure Z CIRCUMFERENTIAL STHAIN DISTRIBUTION ON IMMER SURFACE RING NO. 2 u<sub>0</sub> = 0.0118\*

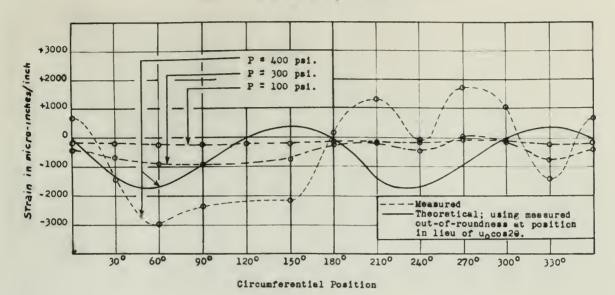
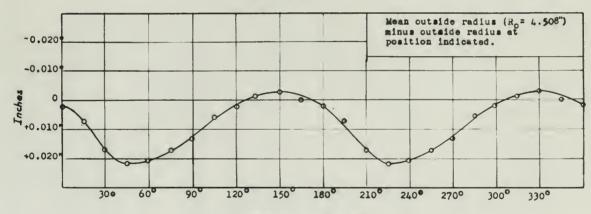


Figure VI
INITIAL CONFIGURATION
RING NO. 2



Circumferential Position

Figure VII VARIATION IN THICKNESS RING NO, 2

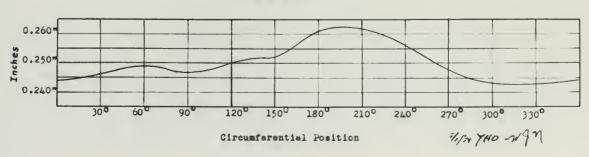




Figure VIII

CIRCUMFERENTIAL STRAIN DISTRIBUTION ON INNER SURFACE RING NO. 3 u<sub>0</sub> = 0.0268\*\*

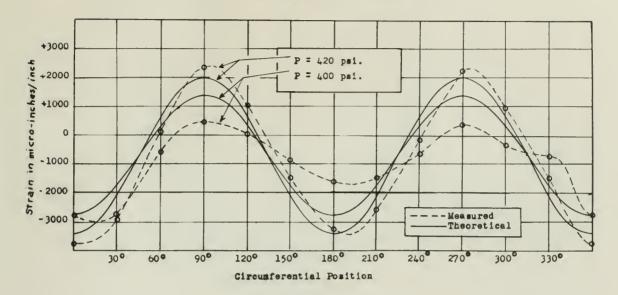


Figure IX
INITIAL CONFIGURATION
RING NO. 3

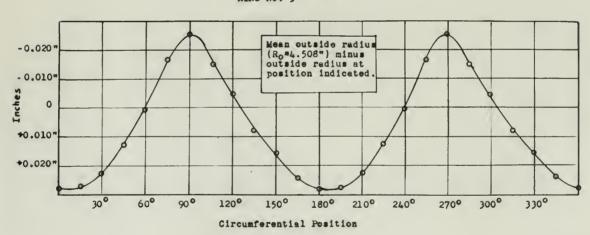


Figure X VARIATION IN THICKNESS RING NO. 3

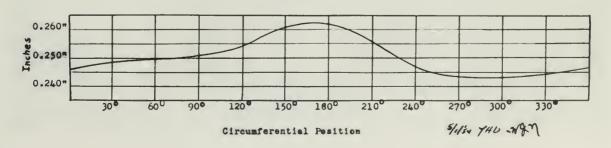




Figure XI

CIHCUMFERENTIAL STRAIN DISTRIBUTION ON INNER SURFACE RING NO. 5  $~u_{0}~\bullet~0.0705"$ 

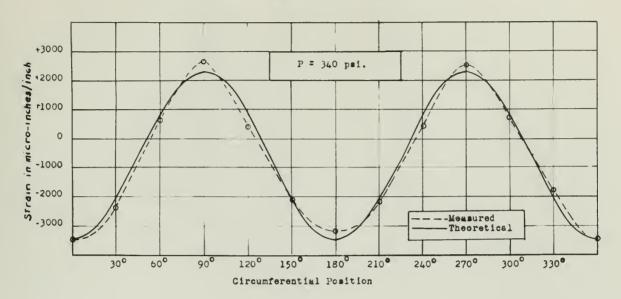


Figure XII

INITIAL CONFIGURATION RING NO. 5

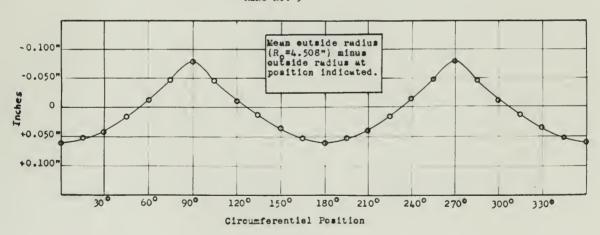


Figure XIII

VARIATION IN THINCKNESS RINC NO. 5

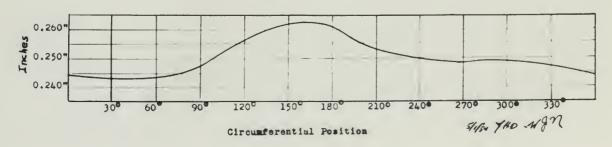




Figure XIV

CIRCUMFERENTIAL STRAIN DISTRIBUTION ON INNER SURFACE RING NO. 6  $u_0$  = 0.075

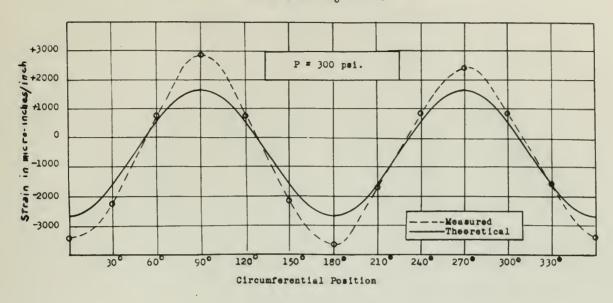


Figure XV

INITIAL CONFIGURATION RING NO. 6

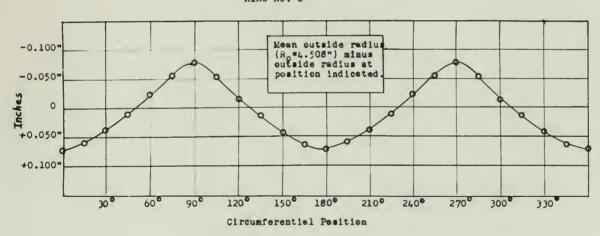


Figure XVI

VARIATION IN THICKNESS RING NO. 6

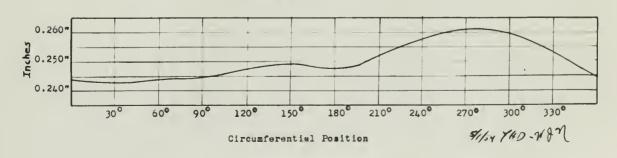




Figure XVII

CIRCUMFERENTIAL STRAIN DISTRIBUTION ON INNER SURFACE RING NO. 7  $\rm u_0 = 0.1535^{\circ\prime\prime}$ 

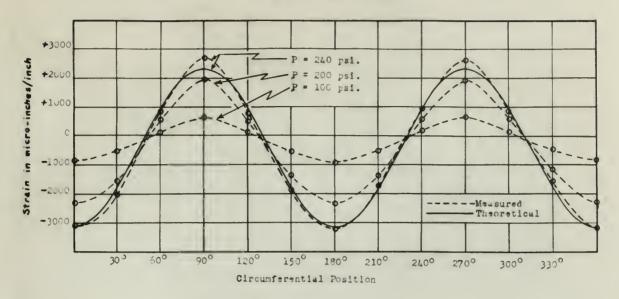


Figure XVIII

INITIAL CONFIGURATION RING NO. 7

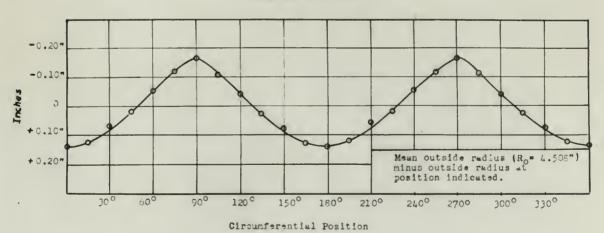


Figure XIX

VARIATION IN THICKNESS RING NO. 7

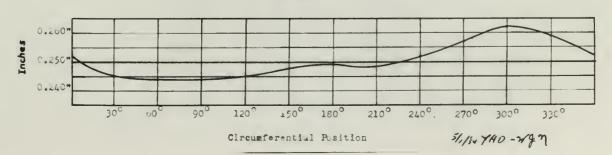
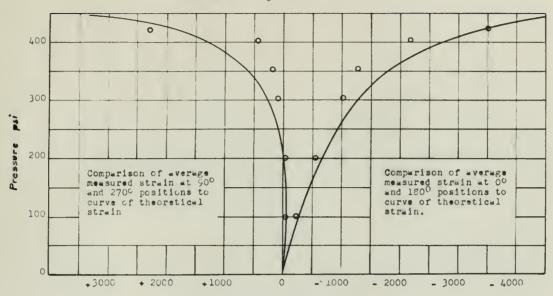


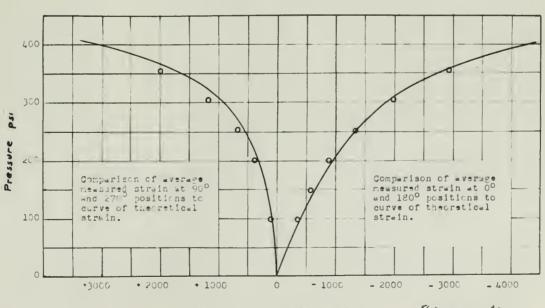


Figure  $\overline{XX}$ COMPARISON OF MEASURED AND THEORETICAL STRAINS NO. 3  $u_0 = 0.027^{\circ}$ 



Strain in micro-inches per inch

Figure  $\overline{\textbf{XXI}}$  COMPARISON OF MEASURED AND THEORETICAL STRAINS RING NO. 4  $u_0$  = 0.048"



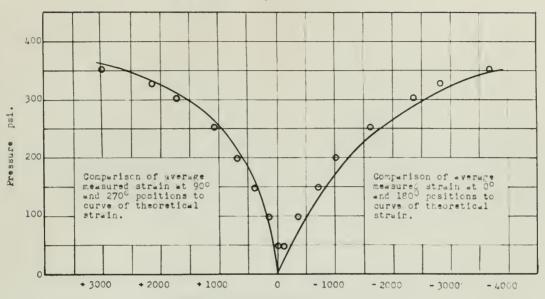
Strain in micro-inches per inch

5/1/50 YAD-NGT



Figure XXII

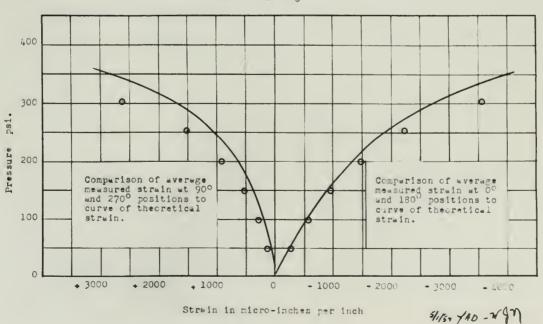
COMPARISON OF MEASURED AND THEORETICAL STARINS RING NO. 5  $\rm u_{\odot}$  = 0.070"



Strain in micro-inches per inch

Figure XXIII

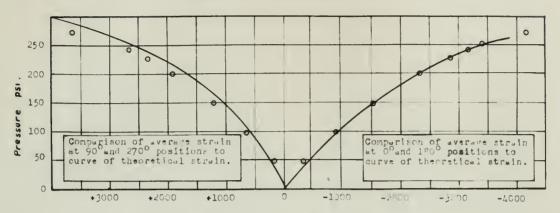
COMPARISON OF MEASURED AND THEORETICAL STRAINS RING NC. 6  $-u_{_{\scriptsize 0}}$  = 0.075\*





#### Figure XXIV

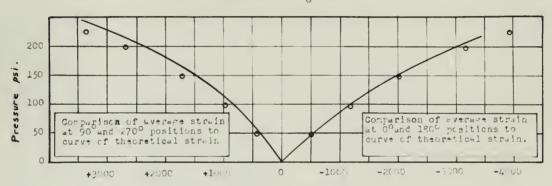
COMPARISON OF MEASURED AND THEORETICAL STRAINS RING NO. 7  $-u_{\phi}$  = 0.1435\*\*



Strain in micro-inches per inch

### Figure XX V

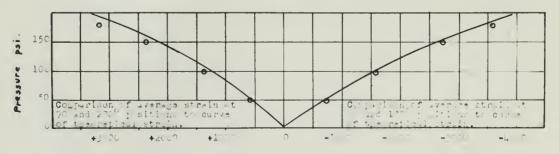
COMPLAISON OF MEASURED AND THEORETICAL STRAINS RING NO. 8  $u_0$  = 0.204"



Str.in in micro-inche per inch

#### Figure XXVI

COMPARISON OF A 2 NOURARY AND THEORETICAL OTRAINS RING NO. ,  $u_{\rm o}$  = 0.423"



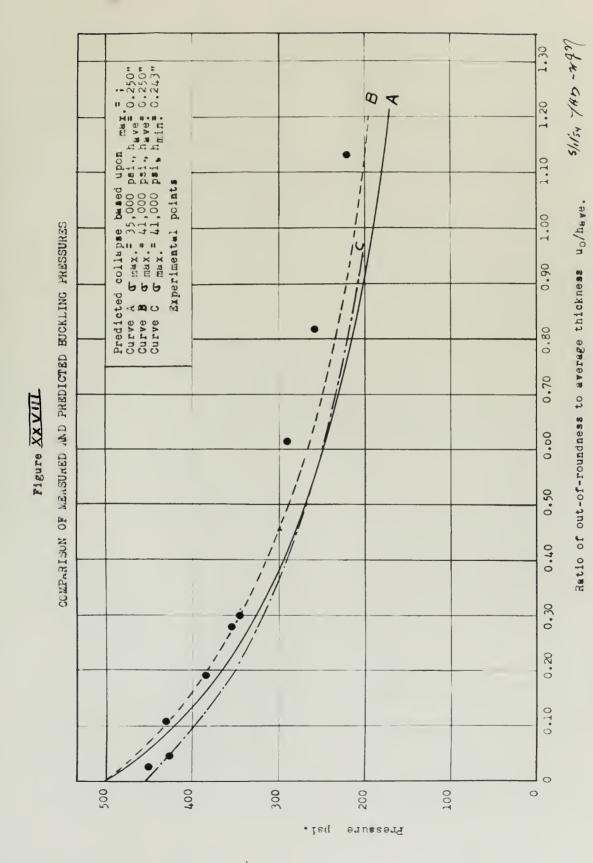
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5/1/5× YAD - WAM



1.10 1.20 1.30 WOK- 144 451/5 Curve of predicted collapse based upon Cmar Ty = 35,000 psi., using have. = 0.250" Experimental points. **ග** 🌘 0.90 1.00 COMPARISON OF MEASURED AND PREDICTED BUCKLING PRESSURES Ratio of out-of-roundmess to thickness - uo/h 0.70 0.80 **%** Figure XXVII 09.0 0.50 0.40 0.30 0.20 0.10 40 0 007 100 0 500 300 200 .leq Pressure







#### IV.

#### DISCUSSION OF RESULTS

### Introduction

For convenience and continuity, the experimental results may be grouped in the following sequence:

- 1. Results of Compression Tests
- 2. Proof Test Data
- 5. Circumferential Strain Distributions
- 4. Maximum Strains
- 5. Collapse Pressures

This classification is convenient in that the significance of any group depends to some extent upon the interpretation and validity attached to one or more of the preceding groups.

## Results of Compression Tests

The results obtained from the compression tests were probably the most significant factors in the correlation of experimental and theoretically predicted quantities.

The data obtained from the tests of the specimens were surprisingly consistent. See Figure III. Values of strain correlate particularly well at high stresses where some deviation might be expected. The possibility of introducing rather significant errors during the resetting of the Huggenberger Tensometers was considered,

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## PTERME O HOTELUATE

## In roduction

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# Herults of Despression toeste

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but a review of the data indicated that increments of strain before and subsequent to a reset were consistent. That the stress-strain curve shown in Figure III is representative of the alloy from which the rings were manufactured is implied in preceding sections. Appreciating the fact that the proof stress and ultimate strength of aluminum alloy varies considerably with the details of the heat treatment and possibly the original lot number, the authors specified that the specimens be obtained from the length of tubing from which the rings were manufactured and that all rings and specimens be heat treated as a group.

Young's Modulus, as determined from the stress-strain curve, was  $10.8 \times 10^6$  psi. and can be compared to  $E = 10 \times 10^6$  psi., the value generally given in handbooks. In the authors' opinion, Figure III justified the assumption of a linear stress-strain relationship up to a stress of 34,500 psi. and a 0.2% proof stress, designated yield stress, of 35,000 psi. Furthermore, it is to be noted that a very distinct departure from linearity did not occur until a stress of about 41,000 psi. was obtained.

These properties were commensurate with those characteristics considered most desirable in the material from which the rings were made. The existence of a linear stress-strain relationship over a large range of stress

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permitted most of the experimental strains to be compared directly with predictions based upon equation (3) without the complication of a decreasing modulus. For extrapolation of the results to steel rings, a plateau corresponding to a true yield stress was desirable. Although the authors did not anticipate such similarity at the time aluminum alloy was selected, the upper portion of the stress-strain curve is in most respects analogous to the compression test curves obtained for mild steel specimens tested by

M. L. Pittman, Jr., and V. W. Rinehart (7).

It may be argued that the remainder of the results would have been of no consequence without the stress-strain data. The use of a standard stress-strain curve for aluminum alloy 618-T6 would have involved an 8% error in Young's Modulus and a 14% error in the proof stress. Furthermore, the shape of the curve above the proof stress is valuable when analyzing the failure of a ring.

## Froof Test Data

The authors have stated that the measured strains at a specified pressure were dependent to some extent upon the gasket and the type of lubricant used between the gasket and the Plexiglas surfaces. Figure IV shows this effect quantitatively. Black rubber-to-metal cement has been designated Lubricant #1 and clear rubber cement as

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Lubricant #2. Although Lubricant #1 was considered most suitable on the basis of a preliminary investigation which has been described, Lubricant #2 appeared to be a reasonable second choice. The two gaskets were of the same dimensions and material but differed in that Gasket #1 had been used several times before while Gasket #2 had not. Relative to Gasket #2, Gasket #1 was very limber and appeared to have a slick, oily surface.

As shown by Figure IV the largest measured strains were attained with Lubricant #1 and Gasket #1. Lubricant #1, Gasket #2 were next in magnitude of strains while Lubricant #2, Gasket #1 gave the smallest measured strains. Considered as percentages, the differences in strains are quite significant. The authors reasoned that the gasket and lubricant were able to affect the strains by changing the magnitude of the friction force acting at the gasket-Plexiglas interface.

On the basis of the results indicated by Figure IV, the authors elected to use a well broken-in gasket in conjunction with Lubricent #1 for the remainder of the tests since this combination more nearly satisfied the requirement that the ring be completely free of restraint at the edges.

A thorough investigation of the friction force at the

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gasket-Plexiglas interface should be a prerequisite for further experimentation based upon this thesis. The objectives of such an investigation should be a consideration of all likely gaskets and lubricants, a comparison of possible combinations with respect to effect upon strains, and a quantitative evaluation of the coefficient of friction characteristic of given combinations of gasket, lubricant and pressure.

### Circumferential Strain Distribution

Figures VI, IX, XII, XV, and XVIII show typical out-of-roundness curves. Of the rings shown in this group, all were deformed intentionally with the exception of Ring No. 2, Figure VI. It is significant that the out-of-roundness obtained in Ring No. 2, while purely arbitrary, is very similar to a configuration given by  $u_0 \cos 2\theta$ . The remainder of the plots are characterized by rather steep peaks in the vicinity of the minimum diameter and shallow peaks at points of maximum diameter. It is to be noted that the steep peaks occurred at points where the deforming loads were applied by the loading machine. The configurations are, however, reasonably similar to a cosine curve of the form  $u_0 \cos 2\theta$ .

Figures VII, X, XIII, XVI, and XIX show the variation in thickness versus circumferential position. It is apparent that the relation of thickness and out-of-roundness at a

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## Circuming Orgin Distribution

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particular station is completely arbitrary. In general, the difference between minimum and maximum thickness is of the order of 0.02". Since the out-of-round plot is derived from the diameters read to the outer circumference, the corresponding configuration of the neutral axis may be assumed to deviate slightly from that of the plot. Since sections of thickness greater than average were generally opposite sections of less than average, the effect of this deviation upon the measured value of un is assumed to be of no consequence except in the circular rings. During a preliminary reduction of data the authors considered the effect which a variation in thickness might have upon the plots of out-of-roundness and predicted strains. plot of out-of-roundness for ding No. 2 was altered to a minor extent. The plots for other rings were affected an insignificant emount. Correlation of measured and predicted strains was not improved.

With respect to circumferential strain distributions essentially three types of results were obtained. Figure V shows an arbitrary distribution while Figure XVII shows a well defined cosine distribution. Ring No. 3, Figure VIII, appears to combine some of the characteristics of the first two types.

The arbitrary distribution occurred in those rings

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which were essentially circular. The theoretical curve shown in Figure V is a plot of equation (3) with the measured out-of-roundness at a particular position substituted for  $u_0 \cos 2'\theta$  and with  $h = h_{ave} = 0.250$ °. A point of interest is the fact that the small peaks which are visible at low pressures define a pattern which would seem to persist up to the maximum pressures obtained. The pattern is characterized by a relatively constant strain over  $60^{\circ}$  or  $90^{\circ}$  of the circumference and a fluctuating strain over the remaining  $300^{\circ}$  or  $270^{\circ}$ ; the fluctuations are a reasonable representation of two cycles of a cosine curve. The fact to be observed is that correlation between out-of-roundness and strain distribution is completely lacking.

Subsequent results demonstrate quite clearly that theoretical and measured strains agree satisfactorily when the initial configuration assumed in equation (3) is actually obtained in the ring. It is possible, then, that the method of measuring out-of-roundness was not sufficiently accurate in the case of Ring No. 2. In appraising the out-of-roundness measurement, it is convenient to visualize the initial configuration of the ring as a series of the form Ro + uo cos 2  $\theta$  + ul cos 3  $\theta$  + u2 cos 4  $\theta$  - - - un cos (n + 2)  $\theta$ . The measurements from which Figure VI

theoretical and meants as numetrate subsecting none than any tiple of the section of the continuation as read to equation (') is not not not not not not the rine. It is possible, then, to the cotton of the uring out-of-relundance we not entrypheatly accurate in the case of size of subsective and the case of size of subsective of the case of size of the rine of the

was obtained reflect only those terms of the form uo cos 20, u2 cos 40, u4 cos 60, etc. It is to be observed that of these terms uo cos 20 appears to predominate. Nevertheless, the assumption of a simple contour,  $R_0 + u_0 \cos 2\theta$ , in equation (3) may not be justified since the effect of odd terms (u, cos 30, u3 cos 50, etc.) is not indicated by Figure VI. On the other hand, the effect of this omission upon the predicted strain distribution is not so serious as might be expected. If a relation corresponding to equation (3) is derived assuming a configuration such as  $R_0 + u_1 \cos 3\theta$ , it will be found that the maximum bending stress is proportional to  $\frac{1}{1-P/P_{crit}}$  where

P<sub>crit</sub> is the buckling pressure of a circular ring into (n+2) lobes. The buckling pressure, P<sub>crit</sub>, increases rapidly with the number of lobes; thus the value of P<sub>crit</sub> for a two-lobe collapse is three-eights of P<sub>crit</sub> for a three lobe collapse and one-fifth of P<sub>crit</sub> for a four lobe collapse. Consequently even if  $u_1$ ,  $u_2$ ,  $u_3$ , etc. are comparable in magnitude to  $u_0$  the effect upon the strain distribution will be considerably less since the bending stress is governed by  $\frac{1}{1-P/P_{crit}}$ . In view of these facts

the arbitrary strain distribution appears to be the result of a rather complicated combination of inadequate measure-

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ment, variation of thickness, and localized surface irregularities or dents.

It follows, however, that a more thorough investigation of essentially circular rings is warranted. Rings could be machined as circular as possible and to a close tolerance in thickness. If the initial contour were then determined precisely, it would be possible to evaluate the effect of deviations from a basic two lobe pattern such as that given in Figure VI. It is the authors' opinion that under these circumstances the method of measuring out-of-roundness used in this thesis would prove useful as a practical measure, especially at high pressures.

Ring No. 3 appeared to be the borderline case. With reference to Figure VIII it is apparent that the circumferential strain distribution at 400 psi. deviated considerably from the theoretical curve, equation (3) with  $h = h_{\rm ave} = 0.250^{\rm s}$ . The distribution is not a clearly defined cosine curve, and the magnitude of the strains are generally below the predicted values. On the other hand, at 420 psi. there was a visible deflection of the ring and the strain distribution assumed a form which, except for a  $4^{\rm O}-8^{\rm O}$  phase shift, compared favorably with predicted values. At 400 psi. the deviations from a pure cosine curve are of the same character as the superposition of harmonics upon

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a fundamental wave form. Here it is possible to reason that the terms  $u_1$  cos 3  $\theta$ ,  $u_2$  cos 4  $\theta$ , etc. are significant relative to the basic two lobe pattern given by  $R_0$  +  $u_0$  cos 2  $\theta$ . At 420 psi a two lobe strain pattern was clearly predominate; this would be expected since as the pressure approaches  $P_{\rm crit}$  for the two lobe collapse pattern, the bending strains become significantly greater than corresponding strains resulting from the superposition of other basic configurations. However, in view of the added complication of the thickness variation and possible localized irregularities the authors do not feel justified in attributing the entire cause of the deviations to an inadequate out-of-round measurement. Again it is suggested that the effect of any deviation from a basic two lobe out-of-round pattern requires further investigation.

The last type of strain distribution, the clearly defined cosine curve, is exemplified by Rings No. 5 and 7, Figures XI-XIII and XVII-XIX. With the exception of Ring No. 6, the plots are typical of the results and correlation observed in Rings No. 4-9. Despite the peaked out-of-roundness curve and the variation in thickness, the correlation of measured and predicted strains is excellent. The manner in which the initial peaks of the strain curve progressively increase in amplitude is clearly demonstrated in Figure XVII. Any deviations from the basic two

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The last egg of strain distinuished, has clustly defined to 5 and 7, thouse Life and LVI-LII. With the recention of fine flat of the file of the file of the flat of the flat

lobe pattern were insignificant at all pressures.

The test of Ring No. 6 differed from the others in that the Plexiglas surfaces were coated with black rubberto-metal cement before the ring was placed in the test chamber. The gasket and outer surface of the ring were coated in the usual manner. This deviation from the usual test procedure was made in order to determine whether or not the friction between the gasket and Plexiglas could be reduced still further. The results of this test are shown in Figure XIV. The correlation of measured and predicted strains should be compared with that obtained in Figure XI since Rings No. 5 and 6 were of comparable out-of-roundness,  $u_0 = 0.0705$ " and  $u_0 = 0.075$ " respectively. Where excellent correlation was observed for Ring No. 5, the maximum strains in Ring No. 6 were as much as 40% above the predicted values. This discrepancy cannot be explained by the authors. Were it not for the fact that the results of Rings No. 4, 5, 7, 8, and 9 consistently plotted along the predicted strain curves, it might be assumed that in all cases other than Ring No. 6 a significant restraining force was present at the gasket-Plexiglas interface. The fact that such consistency does exist would imply that the test of Ring No. 6 was faulty in some respect. The results definitely indicate a need for further investigation of the friction force at

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The test of Ring lo. 6 III read income denses can't the flexigles surfaces were onered with black enginerthese man we hearder was gain out thated themes invest-of chemist. The preset and odder burices of the rand ward cost it in the usual senaer. This doubleston in the senaer To Thomas soling to the Throng some W office the not the trick on business the state and the courts he requese still further. . The results of this to distant in the relation of bettern and treatered It crast as he has two sould after personal or of wome autorite since Kings o. 5 and b mere of constitute of -ni-room mond, To = U.U705" and To = 0.075" respectively. There excellent socrelation was cosmiced for diag 50. 5, and mentions strained in Ring To. o Were a much saying above the sectioned volumes. Inte discrepancy cancer by excluding as the nathors. Norw it one for the fact that the soults of Many No. 4; 5, 7, B, and 9 constituting mother along more rated as the status court tempo escor lie or four bearment of topic it pavers ding the 6 a significent Test total o co was present at the gundent-flexigles interfere. The first our constatement done washe would thenty may have been as man Jo. o. what It alky an some roughest. The family series and property and to the a need for Thirthet three inches of the field that for a

the gasket-Plexiglas interface, such as suggested previously.

Maximum Strains

In those rings which were intentionally deformed strain gages were placed at points of maximum (0° and 180°) and minimum (90° and 270°) diameters. The strains at 0° and  $180^{\circ}$  were averaged and plotted for Rings No. 3-9 on the right side of Figures XX - XXVI. Similarly, the average of the 90° and 270° readings are shown on the left side of the same plots. The theoretical curve is simply a plot of equation (3) with cos 2 9 equal to plus or minus one and  $h = h_{ave} = 0.250^{\circ}$ . The strains at 0° and  $180^{\circ}$  are particularly important in that they are normally used in the prediction of a collapse pressure; consequently, the strains at these positions are given added consideration.

With the exception of Rings No. 3 and 6, the correlation of measured and theoretical strain is entirely satisfactory. On the pressure scale the compressive strains are generally within a range of  $\pm 5$ -1/2 psi. of the theoretical curve; this was the assumed accuracy of the recorded pressure. The tensile strains always appear below the theoretical curve; if the modulus of elasticity in tension were assumed to be slightly below 10.8 x  $10^6$  psi. the tensile strains would also correlate. In view of the consistency noted in Figures XXI, XXII, XXIV, XXV, and XXVI, the authors are inclined to think that this might actually be the case.

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In a sense Rings No. 3 and 6 were special cases. As pointed out Ring No. 3 appeared to be the dividing line between configurations in which the two lobe out-or roundness pattern predominated and those which were affected by variations in thickness, harmonics, and/or local irregularities such as a small dent or gouge. Figure XX shows clearly that the measured strains were considerably below the predicted values up to a pressure of 400 psi; at this point the measured strains literally jumped to the theoretical curve. Figure XX tends to substantiate the remarks made previously; that is, in practical cases of out-of-roundness a two lobe configuration derived simply and directly may allow prediction of strains of acceptable accuracy at sufficiently high pressures, but further work is required before complete justification is obtained.

Figure XXIII shows merely that measured strains for Ring No. 6 were larger than the predicted strains over the entire range of pressures. The consistency lends some doubt to the authors' contention that the test may have been faulty.

In conjunction with the considerations of circumferential strain distribution, the results above indicate quite clearly that equation (3) is valid within the qualifications of the derivation; this conclusion is based upon the behavior of

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Rings No. 4, 5, 7, 8, and 9 in which the assumption of a configuration  $R_0$  +  $u_0$  cos 2  $\theta$  was obviously justified. Collapse Fressure

Figure XXVII shows the collapse pressures of the nine rings plotted versus the ratio of out-of-roundness to average thickness and serves to identify the points shown on Figure XXVIII. The single curve is a plot of equation (4) with  $T_{\text{max}} = 35,000$  psi. Figure XXVIII is more informative in that several variations of equation (4) are plotted; the values of  $T_{\text{max}}$  and h which apply to each curve are indicated in the legend.

Foregoing results (see Figure V) indicate that Rings No. 1 and 2 did not assume a two lobe configuration until the ring was in the process of failing completely; if a stable two lobe pattern existed it was possible over a very small range of pressure. Regardless of the cause of the random strain distribution, Figure XXVIII demonstrates clearly that the failure of Rings No. 1 and 2 could have been predicted by equation (4) in which max is 41,000 psi and h = hmin. = 0.243.

There are two ways in which to view these results. First, it would appear that the minimum thickness, uo as measured, and the point at which the stress-strain curve departs significantly from linearity are the only factors

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to be considered; hence, the use of equation (4) would be justified. This line of reasoning would infer that previous remarks relative to the importance of the basic two lobe configuration are entirely correct and that in practical cases of out-of-roundness one could neglect out-of-round other than that indicated by a simple consideration of diameters. On the other hand it is possible to reason that the variation in thickness was actually not significant; this statement could be based upon the collapse pressure of Rings No. 3, 4, and 5. Then the occurrence of collapse below the predition based upon average thickness would be explained in terms of stress introduced by a superimposed but undetected configuration or by local irregularities. The authors can conclude only that in this case of practical out-or-roundness and arbitrary strain distribution the collapse was predicted by equation (4) using minimum thickness and  $\sigma_{\text{max}} = 41,000 \text{ psi.}$ 

Rings No. 3, 4, and 5 differed from Rings No. 1 and 2 in that a clearly defined cosine type strain distribution was observed before failure. In each case the strain peaks corresponded to peaks in the out-of-roundness plot. Furthermore, the progressive failure which occurred in these rings may be contrasted to the rather sudden collapse of Rings No. 1 and 2.

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Figure XXVIII shows that Rings No. 3, 4, and 5 collapsed at pressures very near to predictions given by equation (4) with  $G_{\rm max} = 41,000$  psi and  $h = h_{\rm ave}$ . These results seem to justify the argument above that the variation in thickness in itself was not significant and that the behavior of Rings No. 1 and 2 should be explained on the basis of harmonics and/or local irregularities. Nevertheless, the authors' only conclusion is that for rings of  $u_0/h$  from 0.10 to 0.30 equation (4) when used with the stress at which marked departure from linearity occurs will predict quite accurately the failures in those rings where an initial configuration of  $R_0 + u_0 \cos 2\theta$  is predominate.

Rings No. 7, 8, and 9 collapsed at pressures consistently above the predicted collapse pressure. Furthermore, stable configurations were obtained in which the maximum compressive stress was considerably above the yield point. Obviously as uo increases, the criteria used in computing the collapse pressure becomes more conservative. This result is explained by the fact that the hoop stress upon which the bending stress is superimposed was less at the time yielding occurred in the outer fibers; in addition, the change in stress with respect to pressure was also less in the rings of greater uo when this yielding began. Then to obtain instability in rings of greater out-of-roundness a larger increase in

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pressure was required beyond the point of initial yield in the outer fibers. The authors conclude that for values of  $u_0/h$  greater than 0.30 and less than 1.10 the predicted collapse pressures are somewhat conservative but would be considered satisfactory for usual engineering design.

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#### CONCLUSIONS

- 1. The properties of aluminum alloy 61S-T6 were particularly well adapted to the objectives of this thesis.
- 2. The most significant problem encountered in the method of experimentation was the reduction of friction at the gasket-Plexiglas interface.
- 3. The relation for predicted strains in thin rings, equation (3), is valid when the assumed configuration, Ro + uo cos 2 θ, is obtained.
- 4. In those cases where the equation for predicted strains is valid and the value of h/D is 0.0285 a failure criteria based upon the stress level in the outer fibers predicts quite accurately the collapse of thin rings in which u<sub>0</sub>/n is between 0.10 and 0.30. For values of u<sub>0</sub>/h between 0.30 and 1.10 the criteria is somewhat conservative but not to an extent which would be considered over-cautious in engineering design.
- 5. From the general trend of the experimental collapse pressures as  $u_0/h$  decreases, the authors conclude that the collapse pressure predicted for perfectly circular rings by the Levy Formula,  $P_{crit} = \frac{3 E I}{R^3}$ , is valid.

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- 2. The most significant problem suscontesed in the method of deposition as the reducation at istation of the contest of the literal and the contest of the c
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#### VI.

#### RECOMMENDATIONS

- 1. Aluminum alloy 61S-T6 should be used in any extension of the experimentation described in this thesis.
- 2. A thorough, quantitative investigation of the friction at the gasket-Plexiglas interface should precede any further use of a test apparatus such as that described herein.
- 3. An investigation should be made for the purpose of determining the effect of deviations from a basic two lobe pattern as measured in this thesis. The rings to be investigated should be of constant thickness and the initial configuration should be known precisely.
- 4. A series of rings, machined as circular as possible and to a close tolerance in thickness, should be tested in order to further substantiate the Levy Formula.
- 5. It is recommended that the scope of this experimentation be extended to include commercial shapes such as I or H sections.

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VII.

APPENDIX

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#### APPENDIX A

#### Details of Procedures

### Selection of Material for Construction of Rings

Initially the authors considered the possibility of using steel in the manufacture of the rings. A length of centrifugally cast steel tubing of 18" outside diameter and 1-3/4" wall thickness was available. However, the expense of constructing a test apparatus to accommodate steel rings was considered prohibitive in view of the uncertainty of the results. Furthermore, it was felt that the visual test chamber made possible through the use of Plexiglas would be of tremendous advantage during the test phase; this innovation was not considered feasible in the preliminary design of an apparatus to accommodate the pressures necessary to collapse steel rings.

The use of plastics was also given consideration. The various types of plastics were gradually eliminated for one or more of the following reasons:

- The relatively low modulus of plastics resulted in very low predicted collapse pressures.
- 2. The ultimate strength was generally low relative to available metals.
- The extent of a linear stress-strain relationship was limited.

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These considerations indicated that the range of pressures over which useful data could be obtained was very limited, and, further, that the accuracy of the results would be questionable unless extreme precautions were taken in instrumentation.

As noted in Section II, aluminum alloy 61S-T6 appeared to satisfy the requirements of moderate collapse pressures, an essentially linear stress-strain relationship over a considerable range of stresses, and availability.

#### Manufacture of Rings

As pointed out in Section II the aluminum alloy tubing as received was cut into lengths several times the intended width of the test rings. Alternatively, the rings could have been machined to final dimensions. However, it is rather doubtful that the edges of the finished ring would have remained planar after the ring had been subjected to deformation in a loading machine and a heat treatment. A ring warped in this manner would tend to bind against the plane sides of the annular test chamber within the test apparatus. Consequently, the machining of the rings to the specified width was scheduled as the last operation in the manufacturing process.

The heat treatment of the aluminum alloy was accomplished by the Forge Shop, Boston Naval Shipyard. Specifically, the

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period at 970° F followed by a rapid quench in hot water at 180°F. The hot water quench was specified as an additional precaution against residual stresses. Actually the danger of residual stresses was not particularly significant in view of the rather thin thickness of alloy being quenched; nevertheless, the precaution was considered worthwhile since a hot water quench does not reduce the tensile properties appreciably below those obtainable with a cold water quench. The quench was followed by a precipitation heat treatment at 350°F for eight hours. The characteristics of aluminum alloy 618-T6 as given in reference (5) are:

Tensile Strength 45,000 psi.

Yield Strength 40,000 psi.

E, Young's Modulus 10x106 psi.

Upon inspection of the sections after the heat treatment, it was found that the magnitude of the out-of-roundness introduced had not changed by any significant amount.

### Instrumentation

The requirements placed upon the type strain gage selected were that the gage be small enough for mounting in the space available and that the gage length be sufficiently short with respect to the strain gradient. The SR-4, type A-7, strain gage satisfied these requirements. The gages

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could be easily mounted within the width of the ring, and, furthermore, a 3/16" gage length was entirely adequate since the predicted stress gradient in the vicinity of points of maximum stress was very small.

A multiple selector switchbox was used to facilitate reading the strain indications. The switchbox was constructed to permit the operator to set the same initial reading on all strain gages.

#### Design and Manufacture of Test Apparatus

The primary concern of the authors in the initial design of a test apparatus was the application of a uniform pressure on the outer surface of the rings without the introduction of restraining forces on the ring edges. An annular test chamber appeared to be the most suitable in this respect. The annulus was designed such that the tolerance between the surfaces and the edges of the ring would be exceedingly small, i.e., order of 0.001-0.002". This would facilitate sealing and yet the ring would remain "free floating" so to speak. From preliminary calculations based on the Levy formula for the collapse of 9" diameter aluminum rings or the 1/4 inch thickness, it was estimated that the test chamber would be subjected to a pressure of approximately 500 psi. Because Plexiglas is beautifully clear and can be obtained in large thick sheets with polished surfaces, it was decided to design the test annulus with upper and

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lower surfaces of this material. This construction would permit visual inspection of collapse and the possibility of obtaining deflection readings. Plexiglas, however, has a low modulus of elasticity and therefore required backing to prevent the surface from deflecting appreciably when subjected to the expected pressures. The top steel web assembly and the bottom steel reinforcing ring as indicated in Figure I were designed for limiting the deflections of the Flexiglas. The hole in the bottom Plexiglas and reinforcing plates was introduced to accommodate strain gage leads. The steel surfaces indicated to be surface ground in Figure I were so designated to provide good contact surfaces between the steel and the Flexiglas. The steel surfaces as received, particularly those of the spacer ring, would not have insured a uniform spacing of the two surfaces forming the annulus.

Although four 3/8" bolts would have been sufficient from considerations of strength alone, it was decided to use sixteen in order to obtain oil tightness.

Originally rubber gasket material was to be used between the spacer ring and the Plexiglas surfaces to prevent oil leakage at the junction of the steel and Plexiglas outside the annulus. However, the rubber gasket would have been compressed in varying amounts around the test apparatus,

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depending on the tension in each bolt upon tightening up. It was possible to circumvent this difficulty by using paper of 0.010" thickness.

The pressure tap was designed to accommodate a 1/4" copper tube fitting. The air release tap diametrically opposite was so placed to vent the test chamber while oil was being introduced.

The cathetometer used to take deflection readings was mounted as indicated in Figure II and Photograph No. (4). The heavy brass plug on which the cathetometer is mounted was machined to fit snugly into the thick walled pipe which had been welded into the center of the top web assembly or the test apparatus; the thick-walled pipe was machined true to an axis perpendicular to the surface of the Plexiglas. A bench mark was established on the web assembly to facilitate taking deflection readings.

### Froof Test of Apparatus

The objective of this phase of the testing was to solve as completely as possible the many unexpected problems of detail which plague any initial effort. In addition it was desirable to establish a standard test procedure to be used during the remainder of the experimental work.

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apparatus was the need for an effective seal between the Plexiglas surfaces and the edges of the test ring. Pre-liminary considerations indicated that the most likely solution would be the use of either a leather or rubber gasket of slightly greater width than the ring. The gasket could be shaped to fold back against the Plexiglas surface when the top assembly was bolted down. See Figure XXIX (a). To facilitate assembly, the gasket could be glued to the outer circumference of the ring prior to insertion in the test chamber.

The following trial gaskets were selected for preliminary investigation:

- 1. A strip of bicycle tire inner tube cut to 3/4" width, 28" in length, and joined at the ends with rubber cement. Results: Not successful because a secure junction could not be obtained.
- 2. Rubber electrical tape applied to the outer circumference with the ends lapped.
  Results: Extrusion of the tape between the Plexiglas surfaces and the edges of the ring occurred at pressures of about 400 psi.
- 3. Leather strip 3/4" wide, 28" in length with junction secured by a special leather cement.
  Results: Not successful because the strength of the junction was unsatisfactory.

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## FIGURE XXIX

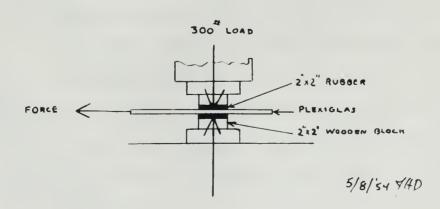
#### DETAILS OF GASKET





## FIGURE XXX

#### DETAILS OF LUBRICANT TEST





4. Truck tire inner tube 9" in diameter cut to 3/4" width with edges beveled as indicated in Figure XXIX(b).

Results: Successful in holding pressures up to 875 psi.; it is interesting to note that even at this pressure the gasket did not extrude. Pressure was not increased beyond 875 psi. for fear of introducing a permanent set in the top Plexiglas surface. There was no junction difficulty in this particular case because the gasket was continuous.

Further experimentation with gasket No. 4 indicated that the 3/4" width was unnecessary and could be reduced to 1/2". The angle of the bevel was changed to 45°. The procedure for cutting the final gaskets was as follows:

- 1. Glue a 2" section of rubber tubing around the circumference of an 11" wooden disk attached to a lathe chuck.
- 2. Place the disk in the lathe and turn at slow speeds. (At high speeds the rubber was torn loose from the wooden disk)
- 3. Hold a sharp, pointed cutting tool at 45° to the edge of the disk and slowly press the tool into the rubber in much the same manner as if turning down wood.

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  - 3. Hole a soarp, potented contitue tool of 45° to the odge of the disk and clowly press the fool late the rubber in muon the wave named as if horself. dres wood.

4. After the cutting blade has passed completely through the rubber, the tool is removed and inserted 1/2" from the first cut, the inclination being that required to produce a reverse 45° bevel.

Gaskets manufactured as above were glued to the outer circumference of the preliminary test rings with clear or black rubber cement. It was thought that a film of oil between the rubber gasket and the Plexiglas surfaces would be sufficient to lubricate the gasket and permit relatively friction free slipping. The first preliminary test ring was placed in the test chamber. Pressures well above the predicted failure pressure were applied without collapse of the ring. The possibility of passing through the first critical collapse pressure was discounted as a complete explanation because without noticeable restraint such could occur only by a combination of ideal conditions and fortuitious circumstances. The apparatus was repeatedly opened to adjust the gasket and, if possible to determine the cause or the restraint. After numerous trials the ring buckled at approximately 550 psi., well above the predicted collapse pressure.

The second preliminary test ring was similarly tested several times without success. At this point the authors

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decided to direct all efforts toward the elimination of the restraining force which prevented the collapse of the rings at reasonable pressures. It was assumed that the restraining force occurred as a result of friction between the rubber gasket and the Plexiglas since without the gasket the rings were found to be completely free when enclosed in the test chamber.

Several types of lubricants were investigated by spreading the lubricant over two rubber 2"x2" squares and sandwiching a piece of Plexiglas between them. A load was applied to the rubber squares by means of wooden blocks placed between the rubber squares and the heads of a loading machine. See Figure XXX. The force necessary to move the Plexiglas under specified loads was observed. The following lubricants were used:

- 1. Number 40 S.A.E. motor oil.

  Results: Plexigles could not be moved by a force less than 40 lbs. when a load of 300 lbs. was applied by the loading machine.
- Silicone Compound DC4.
   Results: Same as No. 1.

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Results: Plexiglas could be moved by a force of approximately 8 lbs. when a load of 300 lbs. was applied by the loading machine.

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- Clear rubber cement applied to rubber and oil film on Plexiglas.
  - Results: Plexiglas could be moved by a force of approximately 6 lbs. when a load of 300 lbs. was applied by the loading machine.
- Black rubber-to-metal cement applied to rubber and oil film on Plexiglas.

Results: Lubricant effective to the extent that the 2" rubber squares would not remain in place under wooden blocks as the load was being applied.

On the basis of the preceding results it was concluded that the black rubber-to-metal cement was the most suitable lubricant. The rubber gasket was cemented to the outer circumference of the preliminary test ring with a large amount of cement. The aluminum ring was then placed in the test apparatus and the top assembly bolted in position. It was noted at this time that the gasket would not remain in position on the aluminum ring but pulled away in the manner indicated in Figure XXIX (c). The top assembly was removed and several strands of light string were passed around the outer circumference of the gasket. See Figure XXIX (d). The beveled edges were observed to fold back uniformily along the surface of the Plexiglas when the ring and gasket were again placed in the test chamber and the top assembly had been positioned and bolted down. See Figure XXIX (e).

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Pressure was applied and the preliminary test ring buckled very close to the predicted collapse pressure.

The test procedure with respect to gasket material, gasket size, and lubrication was thus established. It is worthwhile to note that the best results were obtained when the black cement was applied to the beveled surfaces, the inner surface of the gasket, and the outer surface of the ring. The cement was allowed to dry slightly after application.

In an effort to obtain deflection readings the authors considered testing the rings in two phases. During the first phase clear rubber cement would be used as the lubricant and both deflection readings and strain readings were to be recorded up to the pressure at which collapse was expected. The pressure would then be released and the ring removed for lubrication with the black cement. During the second phase strain readings were to be taken until actual collapse occurred. However, as pointed out previously strains taken during the two phases did not correlate. Furthermore, the cathetometer proved impractical. The third preliminary test ring was strain gaged and tested with various lubricants and gasket material to show that the strains did in fact depend upon these factors. Results of these tests were presented in Figure IV.

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During the proof testing period oil leakage around the bolt holes was noted. A strip of rubber electrical tape 3/4" in width was glued to the inner circumference of the spacer ring. The edges of this seal folded back toward the center of the test chamber and were pressed tightly against the Plexiglas when pressure was applied. Holes were cut in the electrical tape in way of the pressure tape and air release tape. Little or no oil leakage was observed around the bolt holes throughout the remainder of the tests.

#### Test of Compression Specimens

Since the value of E, Young's Modulus, and  $\sigma_y$  were of primary importance in the correlation of experimental data with predicted stress distribution and collapse pressure, it was immediately apparent to the authors that the values of E and  $\sigma_y$  for the material used should be determined experimentally rather than relying on handbook values which represent average data at best.

Four 2 1/2" wide semi-circular sections were cut from the original piece of aluminum tubing to provide the material from which tensile specimens were to be machined. The semi-circular sections had to be flattened before machining; therefore, the sections were annealed prior to the flattening process to prevent cracking. Annealing was carried out as recommended by the Metals Handbook (5).

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sections were heated for two hours at 750°F, then slowly cooled (not faster than 50°F per hour) until a temperature of 500° was reached. Below 500°F the rate of cooling was not important and the sections were removed from the furnace and allowed to air cool to room temperature.

The sections were then flattened in a mechanical press.

No difficulties were experienced in the flattening operation.

Cracks did not occur in the sections and very little springback was observed when the upper head of the press was

lifted from the sections. From all indications, the

aluminum alloy was sufficiently annealed by the process

described above.

To obtain uniformity of physical properties in the flattened sections, they were heat treated along with the ring sections as described in the material related to the manufacture of the rings.

Unfortunately the flat bar specimens were not quite as true as the authors had anticipated, and it was feared that appreciable bending stresses might be introduced in the tensile specimens during the application of loads.

Initial unfairness could have been eliminated by machining the flat surfaces; however, this procedure would not have been too practical since the original well thickness of the aluminum tubing was only 0.250". A further reduction in thickness would have increased the difficulty of mounting

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of Tensometers. It was then decided to use three compression specimens cut from the flattest portions of the section. Since the length of the specimens required was of the order of 2.5", no appreciable difficulty was experienced in finding planar portions of the sections for this purpose.

Three compression specimens were manufactured by the Department of Mechanical Engineering machine shop.

Specification for compression test specimens:

Using the same material from which the rings were manufactured, three specimens are to be cut and milled to the dimensions of 0.84 x 2.53 inches, these dimensions conforming to the proportions of 1 to 3 as recommended by ASTM standards.

The compression specimen test block and two Type A Huggenberger Tensometers were furnished by the Department of Mechanical Engineering, M.I.T. Load was applied to the block by means of a 10,000 pound capacity loading machine.

As recommended by the Metals Handbook, the Tensometers were mounted on opposite sides of the test specimen. The gage points were located symmetrically with respect to the middle of the length of the specimen and not closer to the end of the specimen than a distance approximately equal to the width of the specimen.

It was found necessary to reset the Huggenberger Tensometers at least four times during each specimen run.

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#### APPENDIX B

#### Sample Calculations and Summary of Data

## Calculation of Ro, Radius to Outer Circumference

The radius to the outer circumference of each ring was measured indirectly by fitting a wire of known diameter around the outer surface of the ring, scribing the wire in position, and then measuring the distance between the scribe marks on a 36 " rule.

Then 
$$R_0 = \frac{l}{2\pi} - d$$
, where

R<sub>0</sub> = radius to outer circumference of the ring in inches.

l = length of wrapper wire measured between
scribe marks in inches.

d = diameter of wrapper wire in inches.

Thus for Ring No. 1:

$$R_0 = \frac{28.391}{2} - 0.01$$

The value of  $R_0$  used in the remaining calculations is the average of all measured radii.

## Compression Test

The strains given by opposite Huggenberger Tensometers at a specified load were averaged to avoid errors due to bending. The stress corresponding to this strain was obtained by dividing the load by the original cross sectional area of the specimen.

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The following calculation applies in the case of Specimen No. 1 at a load of 4500 lbs.

Data - Specimen No. 1

	Huggenberger No. 2201			Hugger	Huggenberger No. 2195				
	Calibration Factor 1040			Calibra	Calibration Factor 1051				
Load	Rdg.	Rdg	Rdg	Rdg	Rdg	Rdg			
0 500 1000 1500 2000 2500 3000 Reset 3500 4000	1.50 1.30 1.09 0.86 0.63 0.43 0.20 1.50 1.33 1.11	-0.20 -0.21 -0.23 -0.23 -0.20 -0.23	-0.20 -0.41 -0.64 -0.87 -1.97 -1.30 -1.47 -1.69	1.5 1.24 1.00 0.74 0.50 0.28 0.05 1.50 1.28 1.04	-0.26 -0.24 -0.26 -0.24 -0.22 -0.23	-0.26 -0.30 -0.76 -1.00 -1.22 -1.45 -1.67 -1.91			

Strain = Tensometer Reading in inches/inch

E<sub>1</sub> = Strain in inches/inch given by Tensometer
No. 2201

 $\mathcal{E}_2$  = Strain in inches/inch given by Tensometer No. 2195

 $\mathcal{E}$  = Average measured strain in micro-inches/inch

$$\varepsilon_1 = \frac{-1.91}{1040} = -0.001836$$
 inches/inch

$$\varepsilon_2 = \frac{-2.14}{1051} = -0.002036$$
 inches/inch

$$\mathcal{E} = \frac{(-0.001836) + (-0.002036)}{2} \times 10^6 = -1936 \text{ micro-inches/inch}$$

$$G = \frac{L}{txw}$$

G = stress in psi.

L = load in lbs.

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t = thickness of specimen in inches

w = width of specimen in inches

$$G = \frac{4,500}{(0.201)(0.841)} = 20,500 \text{ psi}$$

The results of the Compression Test calculations are presented as experimental points in Figure III.

#### Circumferential Strains

Except for the case of Ring No. 2 all predicted circumferential strain distributions were computed directly from equation (3).

$$\mathcal{E} = \frac{P R_0}{E h} + \frac{6 P R u_0 h \cos 2 \theta}{E h^3 - 4 P R^3}$$

All factors are defined in SYMBOLS AND ABBREVIATIONS, page v1. For Ring No. 7,  $u_0 = 0.1535$ "; then for P = 240 psi.

$$\varepsilon = \frac{(240) (4.508)}{(0.250)(10.8 \times 10^6)} + \frac{(6)(240)(4.383)(0.1535)(0.250) \cos 2\theta}{(10.8 \times 10^6)(0.250)^3 - (4)(240)(4.383)^3}$$

 $\mathcal{E} = (400.7) + (2754.8 \cos 2 \theta) \text{ micro-inches/inch}$ 

θ	cos 2 0	2754.8 cos 2 0		
00 & 1800	+1	+2754.8	+3155.5	
30° & 210°	+1/2	+1377.4	+1778.1	
60° & 240°	-1/2	-1377.4	<del>-</del> 976.7	
900 & 2700	-1	-2754.8	-2354.1	
120° & 300°	-1/2	-1377.4	-976.7	
150° & 330°	+1/2	+1377.4	+1778.1	

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# Circumitential Strang

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All recommend on STREETS AND ARPREVIATIONS, page 71.
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7.076	-L2777.4	5.4- BOUE	1200 6
1770.1	* F-7557.*	MALE WOLK	150° m

Since  $\mathcal{E}$  has been defined as a compression strain the plotted values become:

Circum	nfe	erential	Position	Strain	in	micro-inches/inch
00	&	180°				-3155.5
30°	&	210°				-1788.1
600	&	240°				+976.7
900	&	2700			4	+2354.1
1200	åc	300°				+976.7
150°	ðc	330°				-1778.1

The circumferential strain distribution for Ring No. 2 was computed using the measured out-of-roundness at each station instead of  $u_0$  cos 2  $\theta$ .

$$\mathcal{E} = \frac{P R_0}{E h} + \frac{6 P R u h}{E h^3 - 4PR^3}$$
 (5)

Data:

at

	Circumfe	erential	Position	u	Sign as determined	by
	00 &	180°		0.0075	equation (5)	
	30° &	2100		0.0800	+	
	500 &	2300		0.0125	+	
	800 &	260°		0.0065	+	
	1100 &	290°		0.0045		
	150° &	330°		0.0125	-	
,	P = 400	psi.				

Since E has been delined an a compression errors the platfied values become:

name/15cm	Sir in mero-	noith of	Coltman
	-3155.5		
	-1788.1		300 1 2100
	7.070+		00 2 200
	+2354.1		907: 008
	+976.7		000E 300°
	-1778.1		0066 \$ 0051

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	-	0.01295"	150° & 500°
			180 DO = 4 Ju

$$\mathcal{E} = \frac{(400)(4.508)}{(0.250)(10.8 \times 10^6)} + \frac{(6)(400)(4.383)(0.250) \text{ u}}{(10.8 \times 10^6)(0.250)^3 - (4)(400)(4.383)^3}$$

Platted Strain

 $\mathcal{E} = 667.85 + 83353.4$  u micro-inches/inch

Substituting data:

C

diroum:	ľel	rential Fosition	in micro-inches/inch
00	&c	1800	-42.7
30°	&	510 <sub>o</sub>	-1334.65
50°	å	230°	-1709.77
800	徳	2000	-1209.03
1100	8	290°	-292.76
150°	Čt.	330°	+374.08

A summary of all such calculated values is given in the form of curves, see Figures V, VIII, XI, XIV, and XVII.

## Maximum Strains

The maximum strains at specified pressures were computed using equation (3). Cos 2 0 becomes +1 for  $0^{\circ}$  and  $180^{\circ}$  positions and -1 for  $90^{\circ}$  and  $270^{\circ}$  positions.

$$\mathcal{E} = \frac{P R_0}{E h} + \frac{6 P R u_0 h}{E h^3 - 4PR^3}$$
 (6)

$$\mathcal{E} = \frac{P R_0}{E h} - \frac{6 P R u_0 h}{E h^3 - 4 P R^3} \tag{7}$$

E for a ring of given  $u_0$  is computed from equations (6) and (7) at several increments of pressure. For Ring No. 5,  $u_0 = 0.070^{\circ}$ ; then at 50 psi.:

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E at Qo and 1800

$$\mathcal{E} = \frac{(50)(4.508)}{(10.8 \times 10^6)(0.250)} + \frac{(6)(50)(4.383)(0.070)(0.250)}{(10.8 \times 10^6)(0.250)^3 - (4)(50)(4.383)^3}$$

 $\mathcal{E} = 234.9 \text{ micro-inches/inch (Plotted with - sign)}$ 

E at 900 and 2700

$$\varepsilon = (50)(4.508) - (6)(50)(4.383)(0.070)(0.250)$$
  
 $(10.8 \times 10^{5})(0.250) - (10.8 \times 10^{5})(0.250)^{3} - (4)(50)(4.383)^{3}$ 

 $\mathcal{E} = -63.0$  micro-inches/inch (Flotted with + sign)

Pressure psi.	Plotted value at	Plotted value at 90° and 270°
50	-234.9	+68.0
100	-507.7	+173.8
150	-654.3	+333.5
200	-1,241.7	+573.9
250	-1,778.1	+943.4
300	-2,539.9	+1,538.2
350	-3,750.7	+2,582.1
400	-6,077.3	+4,741.7

A summary of all such calculated values is given in the form of plots, see Figures XX-XXVI.

#### Collapse Pressures

The curves of predicted collapse pressures were derived indirectly by first plotting equation (4). Stresses at various pressures were computed for several values of uo.

TROO	Saya:	90	26	3

E (50)(4.506) (6.50)(4.303)(0.070)(0.50)
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A cross curve of predicted collapse pressures was then drawn using the values given by the intersection of a single ordinate 35,000 psi. or 41,000 psi. with the curves of stress versus pressure.

To compute one point for stress-pressure curves:

$$u_0 = 0.050$$
,  $P = 50$  psi.,  $h = 0.250$ 

$$G = \frac{P R_0}{h} + \frac{6 P R u_0 h E}{E n^2 - 4 PR^2}$$

$$G = \frac{(50)(4.508)}{(0.250)} + \frac{(6)(50)(0.050)(4.383)(0.250)(10.8 \times 10^6)}{(10.8 \times 10^6)(0.250)^3} - \frac{(4)(50)(4.383)^3}{(4)(50)(4.383)^3}$$

G = 2,090 psi., maximum compressive stress

#### Similarly:

Pressure psi.	psi.
100	4,431
200	10,609
250	15,005
300	21,139
350	30,737
400	50,206

Values for  $f_{max}$ , were computed at several increments of pressure for the following values of  $u_0$ : 0.050", 0.100", 0.150", 0.200", and 0.250". The procedure was repeated using  $h = h_{min} = 0.243$ ".

The results of these computations are presented as curves, Figure XXXI. Shown in the same Figure are ordinates

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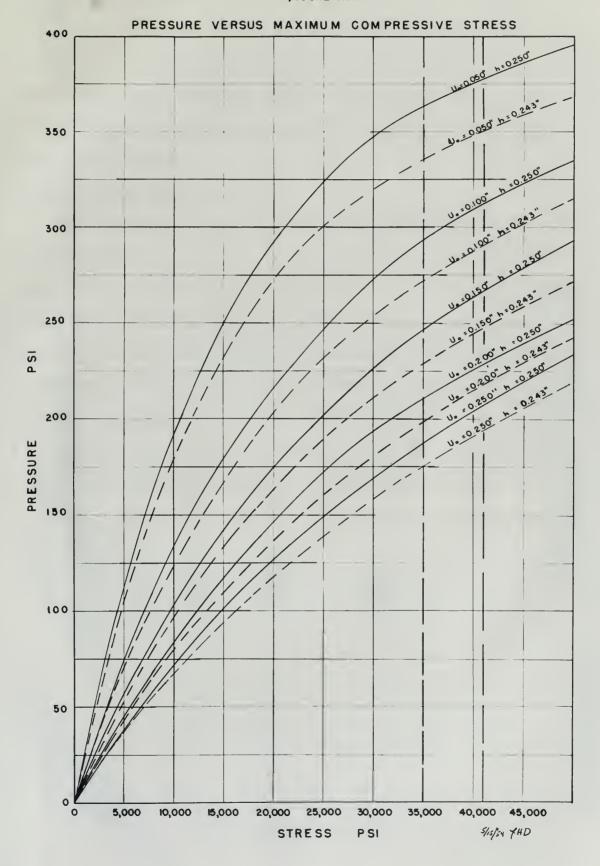
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FIGURE X'XXI





at 35,000 psi. and 41,000 psi. The intersection of pressurestress curve with these ordinates determined the points through which the predicted collapse pressure curves were drawn; see Figures XXVII and XXVIII.

#### Experimental Strain Readings

The strain data was checked for significant errors by plotting measured strains versus pressure for each strain gage. There were no marked deviations from the fair curves which were drawn through the points. These curves were also used to determine the experimental points shown in the plots of circumferential strain distribution in Figures V, VIII, XI, XIV, and XVII.

The measured values of strain shown in Figures IV and XX-XXVI were taken directly from the original data.

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#### APPENDIX C

#### Original Data

Table I is a tabulation of the data taken during the test of the three compression specimens.

Table II is a record of the data recorded during the investigation of the effects of lubricants and gasket material upon the strain distribution around the inner circumference of the aluminum rings.

Tables III - XI contain data relating to physical dimensions, circumferential strain distribution, collapse pressures and diametral readings for each ring.

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	43	时2195	1.60		0.9%	0.5%		0.19	1.49		1.06	,	0,60	0.35	0,10	1.53	1.43	1,18	0.84	07.0	1:0%		-0.12	1.55	0.10				
	Specimen #3	B#2201	1.58		1,26	0.82		0.37	1.59		1.15		0.0	0.46	0.24	1.54	1.40	ויין	0.78	0,000			0.11	1.47	0.43				
Compression		142195	7,58		76*0	17.0		0.03	7.62		1.15		0.69	0.52	0.29	7.55	1.30	1.03	0.80	0.55	reset 50	1.60	1.40	Reset to		0.36	1.45	2 6	-0.15
Table I	#2	H#2201	1.60		1.40	96-0		0.59	1.55		1.05		0.62	0.45	0.22	1.60	1,36	1.10	06,0	0.65	0.35	1.50	1.34		1	0.54	1.53	(	0.39
Data for Stress-Strain Curve in Compression	Specimen #2	142195	1.50	1.24	8.0	0.50	0.28	0.05	1.50	1.28	1.04	0.81	0.57	0.35	0.10	1.50	the fight sales to	CONTRACTOR	And the second second	determinations	deducind	1.50	1.12			0.30	1.50	0.23	
	#1	1岁2501	1.50	1.30	1.09	0.63	0.43	0.20	1.50	1.33	1,11	0.89	99.0	0.45	0.21	1.50	1.30	1.05	0.82	0.56	0.25	1.50	1.01			0.01	1.50	0.02	
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W W		2400	7000 6830 <b>6660</b> <b>658</b> 0	6780	2400	7000 6850 6770 6860		2400	7000 6860 6735 6735 7280
Table II for Preliminary Test Ring	per inch	2100	7000 6900 6800 6790	7010	2100	7000 6890 6840 7055		2100	7000 6880 6800 6820 7345
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	dicated 453	10,120	10,160	10,215	10,120	02666	Can the derived by and separate	10,710	10,460	9,730	9,715	10,430	10,460		#605						
	per inch at pressures indicated 303 403 453	10,270	10,285	10,305	10,200	10,090		10,730	10,545	9,910	9,830	10,470	10,530		Outside Radius = 4.509"						
8 17	inch at 303	10,500	10,515	10,460	10,370	10,310	Agaranie calestininininini esti calestini	10,790	10,670	10,255	10,120	10,530	10,605		Outsid						
ta for Rin	inches per 200	10,610	10,670	10,630	10,640	10,590	Account the encountries of the engineering	10,790	10,750	10,560	10,430	10,700	10,705			9.038	9.035	9.031	9.032	9.033	9.026
Table III Strain Da	Strains in micro-inches	10,780	10,805	10,850	10,860	10,820	over designations and series of the sector o	10,860	10,830	10,805	10,800	10,870	10,840			0	0	6	G	6	0
Table III Dimensions and Strain Data for Ring #1	Strains	11,000	11,000	11,000	11,000	000,11		11,000	000,11	000,11	11,000	11,000	11,000			90-270	105-285	120-300	135-3150	150-330°	165-3450
Dime	o u	0.444 11		0.445	0.444	0.445	- 777.0	0.445	0.446	0.445	0.444	0.444	0.445	= 450 ps1	in inches	9.012	9.00%	9.008	9.016	9.027	9.035
	a i	0.247 0	0.250 0			0.261 0	0.256 0	0.247 0		0.243 0		0.246 0	0.248 0	Collapse Pressure		6	6	6	0	0	6
	Angle	00	300			1200	1500	1800		2400			3300	Collapse	Diameter	0-130	15-1950	30-210	45-2250	60-2400	75-2550

1 1 1 1 2	10° 180 5° 10° 5° 10° 10° 10° 10° 10°	State State	
	307-20 307-70 3-909 8-870 70-540 10-3450	10 382 10 382 10 382 10 382 10 382	
br gao	70°00 70°50 70°50 70°50	20°57 20°57	
4.050 4.050 6.050 6.050 6.050	TO NO.	6.5	-
702-500 702-500	10° 20° 50° 50° 50° 50° 50° 50° 50° 50° 50° 5	P1 17 (4) (4) (4)	
	77,000 77,000 77,000 77,000 77,000	Triboo Triboo Triboo Triboo	
Annual Property of the Parket Property of the	FEE FEE	EEEEE	
	ESSEEEE	PARREL.	
THE STATE OF	444644	garaa E	

Table IV

	Dimensi	ons and St	rain Date	Dimensions and Strain Data for Ring \$2	
o e	Strains	In micro-1	aches per	Inch at press	Strains in micro-inches per inch at pressures indicated 0 99 200 303 403
0.448	11,000	10,820	10,690	10,590	11,670
0.447	11,000	10,810	10,605	10,320	9,550
0.448	11,000	10,780	10,520	20,100	8,030
0.448	11,000	10,765	10,475	20,000	0779*8
877.0	11,000				
0.448	11,000	10,800	10,580	10,250	3,850
3770	11,000	10,885	10,770	10,755	11,160
34700	11,000	10,850	10,750	CAS COL	12,335
8770	11,000	10,825	10,650	10,555	10,930
0.448	11,000	10,920	10,885	17,040	12,720
0.448	11,000	10,905	10,840	10,695	12,030
0.448	11,000	10,790	10,540	10,220	085 66

0.244 0.246

Angle

0,249 0,247

3 900 1200 1500 1800 2100 2400 2700

Outside redius = 4.510" 9,042 9.020 105-285 135-315 90-270 120-300 Dismeter readings in inches. 9.030 9,020 9.050 30-210 45-2250 0-180 15-1950

Collapse Pressure = 425 psi

0.256

0,247

0.243 0.243

3000

0,262

0,261

0.252

· ·	Day Trees	Sept Sept on	Speriod Sec. 70	To extend to	Separate Separate	da in	B.n.	P.
	70 5	70 717	70°470	0	37300	ortho.	akk.o	
	522	10,380	10,600	20,620	17 0000	outro.	O-STE	
	0,000	rosteor	TOTOTO	2087	17,000	TALL.	Desta	
	3 2 0	70,000	10,47	TO Less	27,000	ULL.O	07375	
	dpoporer converse library			Charles on decreasing the same	17,000	924.0	0-250	
	Sec.	7 50	20,580	10,500	17,000	Partie	1000	
	17°77°	30° M22	70 4 10	Tros and	27,000	214.0	0000	
	7 33:	JO SAFO	30,750	72,820	277,000	0.440	10.0	
	J. è	7 67 5	L Ca h	058,00	127,000	Pint.	0-250	
	Ja 230	7 900	20,885	70,050	17,000	0.45	10.20	
	12,030	70,895	30%840	70,905	27,000	0.440	0.7873	
	0.5.0	No. of	30,340	007,03	727,000	DATE:	Child	
					-	Mark Park	Single L	
					-	final ad ag	of palenge	7000000
a towns a tribus	CONTRACTOR		0.00	200	63-530	9,000		- Charle
			4*054	1890	200-202	0.030	7.00	20-11
			9000	200	W	9,080	0	20-230
			9,003	020	171-172	0,000	a p	K
			174111.00		THE REAL PROPERTY.	1270		

Change and them part that the transfer

99 9,000 8,730 9,000 8,840 9,000 8,895 9,000 8,840 9,000 8,840 9,000 8,840 9,000 8,850 120-300 135-315° 150-330°		A CAMP TO THE PROPERTY OF THE						
0.246 0.444 9,000 8,745 8 0.249 0.443 9,000 8,840 8 0.251 0.444 9,000 8,895 8 0.251 0.444 9,000 8,895 8 0.252 0.445 9,000 8,815 8 0.247 0.445 9,000 8,770 8 0.243 0.445 9,000 8,840 8 0.243 0.445 9,000 8,840 8 0.244 0.445 9,000 8,850 8 0.244 0.445 9,000 8,850 8 0.244 0.445 9,000 8,850 8 0.244 0.445 9,000 8,350 8 0.244 0.445 9,000 8,350 8 0.244 0.445 9,000 105-285 9 0.044 0.445 9,000 8,350 8	24	0	66	Strains in	Strains in micro-inches per inch at pressures indicated 200 303 303 353 403 423	per inch a	t pressures	indicated 423
0.249 0.445 9,000 8,730 8 0.249 0.445 9,000 8,950 8 0.251 0.444 9,000 8,895 8 0.254 0.443 9,000 8,815 8 0.262 0.445 9,000 8,750 8 0.247 0.444 9,000 8,750 8 0.247 0.445 9,000 8,750 8 0.243 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 105-285 0.244 0.445 9,000 105-285 0.244 0.445 1105-285 0.244 0.445 1120-300 0 9.041 1155-315			8,745	8,450	7,940	7,690	6,225	5,230
0.249 0.445 9,000 8,840 8 0.251 0.444 9,000 8,895 8 0.254 0.445 9,000 8,895 8 0.262 0.445 9,000 8,815 8 0.247 0.445 9,000 8,750 8 0.247 0.445 9,000 8,750 8 0.243 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 105-285 8 0.244 0.445 9,000 105-285 9 0.244 0.445 120-300 8,850 9,017 150-330 9			8,730	8,385	7,830	7,550	6,280	080,9
0.251 0.444 9,000 8,950 8 0.254 0.443 9,000 8,895 8 0.261 0.444 9,000 8,750 8 0.262 0.445 9,000 8,770 8 0.247 0.445 9,000 8,770 8 0.243 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 105-285 8 0.244 0.445 9,000 105-285 8 0.244 0.445 9,000 105-285 8			078-8	8,640	8,475	8,390	8,450	9,150
0.254 0.443 9,000 8,895 8 0.261 0.444 9,000 8,815 8 0.262 0.445 9,000 8,770 8 0.247 0.444 9,000 8,840 8 0.243 0.445 9,000 8,940 8 0.243 0.445 9,000 8,940 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,850 8 0.244 0.445 9,000 105-285 0 9.072 90-270 0 9.072 120-300 0 9.041 135-3150			8,950	8,960	9,130	9,240	087.6	11,350
0.261 0.444 9,000 8,815 8 0.262 0.445 9,000 8,750 8 0.247 0.444 9,000 8,770 8 0.247 0.445 9,000 8,940 8 0.243 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 ter readings in inches.  50 9.072 90-270 0 9.061 120-300 0 9.041 135-315			8,895	8,840	8,930	8,980	070*6	10,010
0.262 0.445 9,000 8,750 8 0.256 0.445 9,000 8,840 8 0.247 0.444 9,000 8,940 8 0.243 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 ter readings in inches.  9.072 9.072 90-270 9.041 120-300 9.041 150-330			8,815	8,640	8,460	8,360	8,180	7,520
0.256 0.445 9,000 8,770 8 0,247 0.444 9,000 8,840 8 0.243 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,755 8 ter readings in inches.  9.072 90-270 9.071 120-300 9.041 135-3150			8,750	8,460	8,035	State La	7,405	5,760
0,247 0.444 9,000 8,840 8 0,243 0.445 9,000 8,940 8 0,244 0.445 9,000 8,755 8 0,244 0.445 9,000 8,850 8 ter readings in inches.  50 9.072 90.270 0 9.041 120.300 0 9.041 150.300			8,770	067*8	8,070	7,830	7,530	6,410
0.243 0.445 9,000 8,940 8 0.244 0.445 9,000 8,755 8 0.244 0.445 9,000 8,850 8 ter readings in inches.  50 9.072 90-270 50 9.061 120-300 50 9.041 135-315			8,840	8,660	067*8	8,410	8,355	8,860
0.243 0.445 9,000 8,755 8 0.244 0.445 9,000 8,850 8 bse Fressure = 430 pst.  ter readings in inches.  0° 9.072 90.270°  0° 9.071 105-285°  0° 9.061 135-315°  0° 9.017 150-300°			076 8	07689	090.6	9,110	9,370	11,220
pse Pressure = 430 pst.  ter readings in inches.  0 9.072 90-270  5 9.071 105-285  0 9.041 135-315  0 9.017 150-300			8,755	8,520	8,360	8,410	8,660	9,920
readings in inches. 9.072 9.072 9.071 105-285° 9.061 120-300° 9.041 150-330°			8,850	8,735	8,650	8,570	8,280	7,530
9.072 90-270° 9.071 105-285° 9.061 120-300° 9.041 155-315°	ssure ==	430 pst.						
9.072 90-270° 9.071 105-285° 9.061 120-300° 9.041 135-315° 9.017 150-330°	dings in					Outside	Outside Radius = 4.510"	510**
9.071 105-285° 9.061 120-300° 9.041 135-315° 9.017 150-330°	0.6		90-270	8-965				
9,061 120-300° 9,041 135-315° 9,017 150-330°	0.6		.05-285°	8.986				
9,041 135-315° 9,017 150-330°	0.6		20-300	6.007				
9.017	0.6		35-3150	9.032				
	0.6		150-330°	270.6				
8.983 165-3450	8		165-3450	790.6				

					ò			2,530	9,320	11,220	B'BRO	6,110	2,760	7,530	TOTOLO	III STO	0.7.0	080,0	1,330	Bottombal a	
								0,420	0	370	300	7,530	7,405	8,100	Ding P	C	08428	080,4	6,235	VOT.	
						***		0,52	8 410	9*770	8,410	03.5	2177	00 8	080.8	Distance of the state of the st	E 3 NO	TARREL .	7,640	doul de	
								3,50	8 360	3.000	89 130	0,00,8	500.8	2	8,000	9,230	570 cm	17030	Dio P	Marko-prope	State .
Property.	2.0.0	SEO.	1.0.E	0000	8,96,			(%) (%) (%) (%) (%) (%) (%) (%) (%) (%)	00	CAP:	050 3	067 8	00226	0.028	075.00	000	2,000	2000	100 A 200	2.0	at sid
"Sup-au	.100	J 2-37	J. 1-300°	-385	·s.to.			V 55 E	8,755	ONP .	0,848	077	657.8	0.08 <sub>4</sub> .5	4	23	1001 00	047.0	12	2	100
206	JRJ- CAE	2 1	THE PERSON	TOP	8			9,000	8 000 P	0.00,0	9,000	9,200	3,000	9,000	0.00	37,000	9,000	94000	9,000	0	Lan rate
196.0	9.01g	0.0.6	1 000 F	0.00	3-mas	the par port	THE PARTY OF	0.445	0.474	214.0	0.16	0.772	D. EVE	20.00	EXT.0	0.424	0.443	20	D'STY	TOTAL O O O	
				10		or sample	se postere	0.00	0.30	1.0	0.374	0.37=	0.80	184.0	10.50	118.0	0.35	Di-A	0,916	b.	
14-500	Borona	Township.	No-smo	J2-50	0.180	State FO	COLL	2780	2000	SUO.	STE	2000	( h	Tall	730	0	100	200	00	POT.	

5	
1e	
Tab	

					The same of the last of the la	1		
a f	Strain	g in micro	Strains in micro-inches per 99 150	inch at 200	pressures indicated	icated 303	353	378
57770	7,000	6,670	6,460	6,170	5,720	5,140	4,260	3,340
9777-0	7,000	6,765	009*9	6,410	07169	5,800	5,340	07667
977.0	7,000	006,9	6,850	6,855	6,925	060.7	7,420	7,810
0.444	7,000	7,030	7,170	7,350	7,670	8,180	9,025	9,950
0.144	7,000	6,880	6,860	0,88,0	6,955	7,110	7,425	7,820
77770	7,000	074.5	009*9	6,390	6,115	5,700	5,105	
0.445	7,000	6,630	007*9	570 9	5,580	4,900	3,900	d distance are expensive
0.445	7,000	6,720	6,550	6,340	060°9	5,770	5,390	
0.145	7,000	6,950	07659	7,015	7,150	7,470	000,	
0.444	7,000	7,120	7,215	7,420	7,690	8,205	7,980	design the relations
0.444	7,000	6,855	062.9	6,775	6,760	6,820	056,9	Branch of Control
0.4444	7,000	6,710	6,570	6,345	6,100	5,680	5,135	CHARLO CENTRAL DE
re = 383	osi							
					Outsi	de Radius =	4.506	
p-q	1n. in 30° 0.261 0.445 30° 0.254 0.446 60° 0.246 0.444 120° 0.246 0.444 150° 0.246 0.444 240° 0.246 0.445 240° 0.246 0.445 240° 0.246 0.445 300° 0.245 0.445 300° 0.265 0.444 330° 0.265 0.444 330° 0.265 0.444 300° 0.265 0.444 300° 0.265 0.444	TS a.	0 00 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 000 0 1 2 0 000 0 1 2 0 000 0 1 2 0 000 0 1 2 0 000 0 1 2 0 000 0 1 2 0 0 0 0	0 99 7,000 6,670 7,000 6,900 7,000 7,080 7,000 6,880 7,000 6,880 7,000 6,850 7,000 6,950 7,000 6,950 7,000 6,855	0 99 150 7,000 6,670 6,460 7,000 6,900 6,850 7,000 7,080 7,170 7,000 6,880 6,860 7,000 6,630 6,400 7,000 6,950 6,940 7,000 6,950 6,940 7,000 6,855 6,790	0 99 150 200 25 7,000 6,670 6,460 6,170 5,7 7,000 6,900 6,850 6,855 6,9 7,000 7,080 7,170 7,350 7,6 7,000 6,880 6,860 6,880 6,9 7,000 6,720 6,900 6,340 6,0 7,000 6,950 6,940 7,015 7,1 7,000 6,855 6,790 6,740 7,015 7,000 6,855 6,790 6,345 6,7 7,000 6,855 6,790 6,345 6,7 7,000 6,855 6,790 6,345 6,7	0 99 150 200 25 7,000 6,670 6,460 6,170 5,7 7,000 6,900 6,850 6,855 6,9 7,000 7,080 7,170 7,350 7,6 7,000 6,880 6,860 6,880 6,9 7,000 6,720 6,400 6,340 6,0 7,000 6,950 6,940 7,015 7,1 7,000 6,855 6,790 6,340 6,0 7,120 7,215 7,420 7,6 7,000 6,855 6,790 6,345 6,7 7,000 6,855 6,790 6,345 6,7	0 99 150 200 252 303 7,000 6,670 6,460 6,170 5,720 5,140 7,000 6,850 6,855 6,925 7,090 7,000 6,880 6,860 6,880 6,955 7,110 7,000 6,630 6,400 6,340 6,115 5,700 7,000 6,720 6,340 6,340 6,090 5,770 7,000 6,855 6,790 6,745 7,470 7,000 6,855 6,790 6,345 6,100 5,680 7,000 6,855 6,790 6,345 6,100 5,680 7,000 6,855 6,790 6,345 6,100 5,680

90-270	105-2850	120-300	135-3150	150-3300	165-3250
9.102	660.6	690.6	9.028	8,986	076.8
0-1800	15-1950	30-210	45-2250	60-240°	752550
	9.105	9.099	9.099	9.099	9.00% 9.00% 9.028 8.986

8.910 8.953 9.006 9.047 9.075

16-		1	Į.	1	1	1	1		0	3,420	7,870	ole.	3,300	思	
	100		000,00	9	1000	N.200	2	FOLL F	D	0,000	· 180-7	5,360	200	2	
	es. = spillet opinico	2000	096,0	307	シャイ	27.2	1,900	2000	1,570	O Linu	7,080	5,800	170		140
	50	1110	2077		TEST.	6,090	S/Joh	o'ny	0,006	1,820	100 350 N	OLI, o	22.72	T	4 9118 101
		23/6	0,110	200	47007	0.760	0,000	06 Lab	- C.	7,250	6,000	0110	6,170	SCO STATE	AT Dete
20.00 min. s		10000	0.70	d'ann	000,00	9,350	0,100	50000	Der de	44744	00.50	50040	6,160	(A)	ons enote
****		0,710				0,000	10000							do or service	
TOPPER, TOPPER, TOPPER, TOPPER, Advantage	7	9.5000	owin.	1000	000,00	o ton	29	27000	147000	00000	es	1/200	17,000.0	O SERVICE OF	
	despisor	- Original												Be	
TEETE		0.00	1	100	20.0	10	F16.9	.0	No.	0.00	0.00		10.0	4.	
J. S.	- delice	300			- Calo	16	180	2000	200	0 00	00	1	0	and the	

Table VII Dimensions and Strein Dete for Ring #5

353	5,250	6,455	2,880	12,100	9,580	6,760	5,380	7.595	9,590	11,905	8,965	25		¢,					
328	6,120	9,960	9.495	11,245	9,295	7,200	6,200	7,130	9,320	11,060	9,530	7,485		= 4.508 #					
dicsted	6,630	7,260	9,280	10,800	9,170	7,470	6,650	7,430	9,200	10,625	9,320	7,710		de Radius					
ssures in	7,390	7,750	9,030	10,140	000 6	7,900	7,360	7,880	9,030	9,990	9,075	8,090		Outside					
inch at pressures indicated	7,880	8,100	8,930	9,720	8,925	8,210	7,860	8,215	8,960	009.6	8,965	8,340							
s per in	8,290	8,400	8,880	9,415	8,890	8,470	8,260	8,470	8,920	9,330	8,915	8,560			9	M	4	-	o os
Strains in micro-inches per 49 99 150	8,625	8,650	8,860	9,175	8,890	8,695	8,605	8,710	8,910	9,100	8,885	8,765			8.856	8.923	8.994	9.041	9.122
sins in m	8,910	8,870	8,860	9,020	8,925	8,875	8,850	8,900	8,930	8,955	8,900	8,920			90-2700	105-2850	120-300	135-315	165-345
Str.	9,000	9,000	9,000	00006	0000.6	0000.6	00006	0000.6	00006	9,000	00006	0000.6	pst.	hes	0	10	2	M =	16
in.	0.444	0.441	0.444	0.445	0.445	0.444	0.443	0.445	0.445	0.444	0.44 5	0.445	re = 365	Dismeter readings in inches	9.138	9.122	6.097	9.046	8.920
in.	0.244	0.243	0.243	0.247	0.256	0.262	0.261	0.253	0.250	0.248	0.249	0.247	Collepse Pressure =	or readin	0	0	0 0	0	0
Angle	00	300	009	006	1200	1500	1800	2100	2400	2700	3000	3300	Collap	Dismet	0-1800	15-1950	30-210	45-2250	75-255

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720-200 720-200 720-200 720-200

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	Par taryin	MALE SANGE STATE OF THE SANGE	1000	078	00	- 1		Differen	MA BOND TAN	STATES STOPPING - 6-503	-	
octo.	SARAT SAL	and the measures with her	Step.									
30	£44.0	0.46		0.920	8,965	9.380	B 3000	0.090	7.50	3, mg2	STT2	
000	16.0	2 14.11	7,000	0.00,5	100 m	0,900	2000	270.4	05/76/2	01210	1,10	
100	dil.	alla_o	5000	Edg.	2,100	Nº 290	7,600	4 0 s	Johns	13,060	1 . LE	
8	0.290	D 442	3,000	0.00	01,50	y 350	035,8	0.0	2008	014	24230	
200	1000	Sand D	4	E 450.	0.720	9**40	25	0.380	J. J. D	7,370	2,550	
20	231.0	2544.0	9,000		·	021.6	9,840	1° 20	F 120	6,100	27380	
300	135.0	110.00	7,000	. 618 a	(10.5	(J)	ore,	7,460	. 7	00000	037.	
0	945 P	D. 11.5	9,000	8,785	090 cm	0,000	6,355	040,0	3.730	- 81237	0.05	
0	0.00	24.5	7,000	4,000	30 Td2	8,425	0.1.0	30,240		10 }~~	317,310	
100	245.D	0.000	000.7	000.5	038,5	9.880	6,330	6,000	7,300	- 6 mile	7.500	
No.	6.96.5	O'THE	4,000	0170	059,6	000,0	ons,	7.930	100 E.F	0200	1000	
-0	-144-5	MI.0	9,000	O.E. a.d.	30	2,240	039,7	3,300	~ (%)	ortad	2.380	
1	į.	* 10 kg	C	46	Show Trees	T20 100	00	\sqrt{13}	(	150	~	
							+	A Company	2			

	16
	Ring
	for
	Data
Table VIII	Strain
E-di	and
	ofmensions.

Angle						now duch	Section to Contract the	での中のかかかかか	
	9 4	A A	0	Strains in	miero-inches	per men 150	at pressures	252	303
00	0.244	0.444	00016	8,740	09768	8,105	7,580	6,850	5,580
300	0.243	0.445	00046	8,780	8,560	8,290	7,945	7,475	6,725
009	0.244	0.445	000066	8,960	8,950	8,970	08046	9,290	9,770
006	0.244	0.445	000 6	9,155	9,340	9,610	10,035	10,690	11,860
1200	0.248	0.445	000 6	066 8	06658	9,020	9,120	9,315	9,760
1500	0.249	0.445	00066	8,830	3,600	8,340	8,005	7,540	6,825
1800	0.247	0.445	00056	8,720	8,390	7,975	7,445	02969	5,305
2100	0.252	0.445	000 6	8,840	8,565	8,490	8,240	7,885	7,310
2400	0.257	0.445	00066	8,995	9,015	9,075	9,200	9,410	068.6
2700	0.261	0.445	00066	9,100	9,230	9,430	07726	10,330	11,410
3000	0.260	9777:0	000066	8,990	8,980	07056	9,115	9,330	098*6
3300	0.253	0.444	000 %	8,870	8,705	8,520	8,280	7,950	7,410

Collapse Pressure = 345 psi.

Outside Radius = 4.506"

	\$ \$5.00 \$5.0	8.908	8,986	9.042	8.910	9.142
	90-270	105-285°	120-300	135-3150	150-3300	165-3450
Diameter readings in inches	9,158	9.134		9.038	396.8	8.905
Diameter	0-180	15-1950	30-2100	45-225	60-240°	75-255

			7	10000	17,11	C	730	508,5	6,32	33.60	7 4 7	·	2500	53,450	0,	
		AND TO WAR	010	2331)	0,540	9,410	88, 7	070	7,50	25	20,690	3,250	72425	028,0	575 40770F	
		O'CETTON DEST	υr 	0,11	077.2	0,0	01	24.75	50 50	9,750	720,07	030%	7,945	7,580	S O	
				Description of the second	Contract of	70.	8,400	7,07	93.60	3° mso	9,610	200	8,240	8,105	1 0 I	201.50
6.073	00 m		87148	e 30	0,230	8,015	(1) (0) (0)	8,500	100g H	N*880	3,340	8,950	2460	8, 60	edan'-esola	True Tor Him
732-3.2	JO0		0,0,0	00 CO	7,000	( P & 8	0,18,8	120	F 30	SEP .	-178	3 60	0000 < 50	8 74	CV CV CV	PT ALL
		1.15	000	500,0	93000	0,000	000	00	3,000	3,000	9,000	9,000	3,000	9,000	0	outranial)
11-152, 1-100 10-170, 1-100 10-170, 1-100 10-170, 1-100	Party.	THE REAL PROPERTY.	0.10	DON'T	TOTAL S	2-	21.0	0.475	0.172	0.145	- Orette	0.0	C. 1. 1	10.10	E =	
4 4 5	0 0 0	of hereigh	535.0	(6)	T. T. T	P85.0	0.092	D10.0	D10.0	24C.0	AA. D	o'est	0.243	1-4.6	A or	
Service of the servic	101-17	DA	000	2000	o'data	Same S	C O LO	Jest'o	000	Se Contraction	000	100°	00	200	edifo	

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	Ring
	for
h-46	Data
Table I	Strain
F. 1	and
	Ofmensions.

			derendendende	THE PAST OFFICE PARTIES AND ASSESSED.	Concrete Laboration agency & spirite		Support of the Suppor	and desiries			
Angle	Fo.	0 th	Stre	ains in 1	alero-in 99	ches per 150	inch at 200	Strains in micro-inches per inch at pressures indicated 49 99 150 200 226 242	indicat 242	ed 273	288
00	0.252	0.444	000066	8,695	8,160	7,510	6,700	6,230	5,890	4,920	3,775
300	0.245	0.444	00006	8,850	8,465	8,010	7,460	7,180	096,9	6,375	5,850
609	0.244	0.443	00056	9,020	9,130	9,280	9,550	9,735	08866	10,300	10,655
900	0.244	0.444	000,6	9,140	9,630	10,210	10,950	11,380	11,700	12,725	14,110
1200	0.245	0-444	00066	8,990	011,6	9,260	9,500	09966	0,770	10,150	10,450
1500	0.248	0.443	00006	8,850	8,460	8,130	7,630	7,340	7,140	6,590	060*9
1800	0.249	0.444	00066	8,685	8,090	7,460	6,635	07169	5,790	7,2760	3,510
2100	0.248	0.444	9,000	8,790	8,485	8,110	7,660	7,420	7,260	6,810	6,465
2400	0.252	0.444	000 6	9,010	9,150	9,290	9,570	9,750	006 6	10,355	10,780
2700	0.257	0.444	000 6	9,230	089 6	10,200	10,910	11,330	11,620	12,570	13,590
3000	0.262	0.443	000,6	8,985	9,130	9,295	9,560	071.6	9,815	10,210	10,575
3300	0.259	0.442	000 6	8,800	8,520	8,220	7,820	7,585	7,430	7,025	6,730
	To a Constitution of the Party		200 22								

Collapse Pressure = 290 psi

mtside Radius = 4.508"

Outside R.						
	8.679	8.793	8.929	6.067	9.168	9.265
	90-270	105-2850	120-300	135-3150	150-330	165-345
liameter readings in inches.	9.293	9.259	9.155	9.052	8,905	8.775
Diameter re	0-180	15-195	30-2100	45-225	60-240	75-255

						reo?.1 - guiña
ds. 6	A-189	700. p	\$1.927 \$1.927	8,793	(A) . 8	1 1000 2700
22 - 1	J-90-330	132-314	00	702	30 × 17	
SALVE	8,488	\$1050	9.155	6.6	0.20	Minist in Inches
No.	SHE	200	aline.	-142	- Marie	-

3,507 3,507 3,507 10,50 1,000 10, 2,173 2,100 2, 15. 20 12. 30 12. 30 12. 30 13. 30 10 3,780 1,870 2,370 2,320 2,320 2,320 2,320 2,320 2,320 2,320 8,730 8,770 8,770 8,730 8,730 8,730 0,210 Ot à 91,500 81,785 81,785 9 tho 200 0,0 3530 9,000 000,0 3,00 0001 COO. 2000 ,000

The second secon

			Dimension	Dimensions and Strain Data for Ring #8	in Data for	Ring #8				
Angle	,a =	o Si	Strai	ns in aicr	Strains in micro-inches per inch at pressure indicated 22 49 99 150 220	I inch at	pressure in	dicated 226	242	25.22
00	0.263	0.445	00006		est very cyclestic eatherways and east control of	فالكيا ويستحسبون فارتبه فيكهونها والإسماقية والمساوية	to by the same state describes that the state of the	to the section of the		College day the eds sor for pur
300	0.250	4777-0	000066	8,660	8,240	06952	6,935	6,570	6,250	5,940
009	0,253	0.445	00066	9,075	9,165	9,325	009*6	9,770	006 \$ 6	10,050
006	0.250	0.445	000066	0076	9,930	10,635	11,580	12,200	12,705	13,260
1200	0:243	0.444	00066	9,110	9,310	9,650	10,170	10,530	10,810	011,11
1500	0.249	0.445	000066	8,730	0,74,8	3,100	7,620	7,360	7,185	7,040
1800	0.246	0.445	00066	8,470	7,800	6,955	5,820	5,070	4,385	3,540
2100	0.244	0.445	000066	8,680	8,260	7,770	7,040	6,630	6,330	6,050
2400	0.243	9770	9,000	9,030	9,215	06766	064.6	10,040	10,230	10,440
2700	0.244	0.445	00006	0,440	10,010	10,775	11,310	12,520	13,110	13,860
3000	0.247	0.445	00016	9,075	9,220	0946	9,835	10,080	10,275	10,465
330°	0.257	77770	000*6	8,675	8,310	7,835	7,240	6,870	6,585	6,320
Collap	Collapse Pressure = 257		ដូច			-				
Diamet	er readin	Diameter readings in inches	nes			Outside R	Outside Radius = 4.509"			
0-1800	0	9,386		90-270°	8.571					
15-1950	0	6.341	105-	105-285	8.686					
30-2100	0	9.207	120	120-300	3.847					
45-2250	0	9,066	135-	135-3150	9.026					
60-2400	O	3.879	150-	150-3300	9.167					
75-255°	0	8.659	165-	165-345	9.286					

		Cota	T 3 8 CT	0.0	0.0	E AL	102 cos	12
		77		00 d	,00	75 102		t
		TO. 65	12.00 E	0,000		20,000		3-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1
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	Out. P. din - (		70,70		27.h.s	3) (01	2000	10 T 10 10 10 10 10 10 10 10 10 10 10 10 10
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7 17 ° ° ° · · · · · · · · · · · · · · · ·			2 0	ි ට ට්ටා	0 7 8		3 %	
100-	2	0.00	0000	0,0	ໃດ ໃດ	3,000		
5.00 S. C.	SOTTED BESTON SELECTION IN SELECTION	799-0 0-044		0.00	0.10	10	0.44TE	24.0
	the parties							
4 5 5 6 6	Destabl	100	18		E Z	7000	6 2 X	S C

Dimensions and Strain Data for Ring #9	Strains in micro-inches per inch at pressures indicated.	8,290 7,425 6,260 5,380 4,560	7,390 6,910	9,395	9,620 10,430 11,490 12,320 13,130	9,190 9,435 9,820 10,140 10,420	电子程序 经基本的 人物 用于上处 医甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基甲基	8,290 7,415 6,280 5,430 4,630	7,670 7,285	9,160 9,390 9,745 10,040 10,310	9,570 10,310 11,275 12,025 12,750	9,180 9,440 9,850 10,200 10,520	8,650 8,215 7,645 7,260 6,930	Outside Radius = 4.510"		90-270° 8-401	105-285° 8.549	120-300 8.798	135-315° 9.042		150-330 9.259
Dimensions	Strai	000.6	9,000	00006	000*6	00006	00066	000*6	000°6	000066	000,6	00066	000,6	w-f	***				0		
	o H	0.443	0.444	0.444	0.444	0.443	0.444	0.444	0.445	0.444	0.445	0.443	0.443	re = 220 ps1	gs in inches.	9.532	9.452	9.254	9.021		8.794
	T T	0.248	0.244	0.2/4	0.243	0.244	0.252	0.261	0.261	0.258	0.251	0.249	0.250	collapse Pressure	Diameter readings	0_	0	0	0	0	
	Angle	00	300	009	006	1200	1500	1800	2100	2400	2700	3000	3300	Collap	Diamet	0-180	15-1950	30-210	45-2250	-	00-240

	ر. د	8.	9	-02	2	R	02	-	13	90	TO	6	0	0 1	
	- 0.	72		-3 -3 	TO 3 T	Days or	2		TIPLE	- C.	70,01	-	4000	os os de chair	
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			0,000	7. 3.hr	9:11=	7,50,00	0 17		73	17,400	9,180	0, 2,5	03840	or good st	ATLE S
6.5.8 6.5.8	8	on on	0,240	0.5500	015	8,220	22.7		m.	10, 20	3000	8,05	A. 1522.	2 Translation - 23	CI
-340	our sup	6000	9,130	ONE P	STRO	0,5,5	0. 8	- Application of the second	( ,	27.530	5	577 60	974.5	ing the property and	A Charles and the first to the first
	2000	9,000	0,000		A TOWN	2000	33,000	000000	0,00,0	0,300	000 20	036,0	3,1000	157	Interestation of the last
	117.0	1	644.0	0.1.5	44.0	0.116	ОТТР	· .		2.646	0.44	434.0	ELL.O	E.	
	Orthonical deposits	200	0.00	0.27	81.0	135.0	198.4	122	JA2.0	0.373	4.5.0	445,0	25.0	P. D.	
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CONTRACTOR

## AFPENDIX D

## Literature Citations

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